Special Publication SJ93-SP13

PROCEEDINGS AND CONCLUSIONS OF WORKSHOPS ON: SUBMERGED AQUATIC VEGETATION INITIATIVE AND PHOTOSYNTHETICALLY ACTIVE RADIATION

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Edited by

Lori J. Morris
St. Johns River Water Management District
and
David A. Tomasko
Sarasota Bay National Estuary Program

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EXECUTIVE SUMMARY

Derek S. Busby, Project Director
Indian River Lagoon National Estuary Program
and
Robert W. Virnstein, Ph.D.
St. Johns River Water Management District

Submerged Aquatic Vegetation (SAV) is perhaps the most important habitat in the Indian River Lagoon system. SAV ecosystems (seagrass and macroalgae) are highly productive areas that exhibit levels of primary productivity that often exceed highly manipulated croplands. SAV also provides: (1) crucial habitats for numerous invertebrates and fishes; (2) major contributions to the Lagoon in detrital food web; (3) critical areas for nutrient cycling; and (4) sediment stabilization and shoreline protection. Maintaining and enhancing this critical habitat is a goal of both the Surface Water Improvement and Management (SWIM) Program and the Indian River Lagoon National Estuary Program (IRLNEP).

Over the past 20 years, losses of SAV coverage in some areas of the Indian River Lagoon have exceeded 95 percent, while the SAV acreage in other areas has remained stable and highly productive. Reduced light transmittance, increased particulate loadings, and epiphytic growths have all been implicated in this loss of SAV.

The Submerged Aquatic Vegetation Initiative (SAVI, which is included in Appendix I) is critical to the management of the Indian River Lagoon. This initiative represents our efforts to protect and restore the most critical habitat component of this diverse estuary. Seagrasses and other submerged vegetation are not only important from an ecological standpoint but are also recognized as an indicator of the overall health of the system.

The SAVI has a simple goal: "to maintain or improve water clarity to a point that submerged aquatic vegetation could increase bottom coverage throughout the Lagoon to a depth of two meters." This goal and the concepts outlined within the

SAVI are built upon past work both here and in other parts of the country. In the Indian River Lagoon region, the use of submerged vegetation as an indicator of water quality was first explored during a workshop hosted by the South Florida Water Management District during November of 1990. That workshop served to summarize the scientific knowledge regarding the light requirements of seagrasses and examined the potential effects of reduced water transparency upon the survival, distribution, and abundance of seagrasses. It also explored the ability of existing water quality standards to protect seagrasses from deteriorating water quality.

During July of 1992, the IRLNEP sponsored a follow-up workshop to allow scientists, planners, IRLNEP project staff, and various agency personnel to discuss and develop consensus about the SAV Initiative and to explore the means to accomplish the five tasks outlined within the initiative. (The proceedings of the 1992 workshop are incorporated into this publication.)

These tasks include:

(1) Conducting an inventory of SAV throughout the Indian River Lagoon system.
(2) Analyzing the factors causing loss of SAV.
(3) Developing recommendations for controlling factors causing SAV decline.
(4) Developing recommendations for strategies and methodologies to maintain existing SAV habitat and to restore or rehabilitate SAV in impacted areas.
(5) Developing recommendations for the continued assessment of SAV.

At the 1992 workshop, participants agreed that the St. Johns River Water Management District (SJRWMD) will complete the 1992 SAV inventory for the Lagoon system and that the analysis of factors causing SAV loss will be addressed by existing and proposed water quality monitoring programs. The last three tasks will be completed through the SAV Initiative.

A consensus was reached at this workshop on the importance of photosynthetically active radiation (PAR) in the Lagoon. PAR is a measure of the light available for photosynthesis. All plants, including submerged species such as seagrasses, require light to survive and flourish. Where light penetration is reduced, seagrass acreage is also reduced, becoming either nonexistent or largely limited to shallow waters. PAR data can be used to calculate the coefficient of light extinction, (*K* value) as a measure of the transparency of the water column. The higher the coefficient of light extinction, the less light will penetrate the water column.

As proposed by the SAV Initiative, PAR data can also be used in combination with water quality data to calculate "target" concentrations for certain parameters known to affect the transparency of the water column. These parameters include total suspended solids, chlorophyll, and color. These target concentrations can then be used to focus management activities which reduce the amounts of critical pollutants entering the Lagoon from the watershed. Reduced pollutant concentrations will in turn increase transparency, allowing deeper light penetration, and providing conditions favorable for seagrass reestablishment.

The SAV Initiative was conceived with the idea of developing standards to measure water quality on a watershed basis. At the workshop, participants agreed that the Initiative supports similar on-going research in the Chesapeake Bay, as well as that being conducted by Dr. Judson Kenworthy of the National Marine Fisheries Service.

Essentially, the SAV Initiative will employ a model developed by Kenworthy during his dissertation (1992). Kenworthy's proposed model (see Appendix II) for improving the transparency standard incorporates a five step process and is intended to be waterbody specific. These steps are:

> "(1) the aerial coverage of the seagrass species pool is determined for the Indian River Lagoon. This aerial coverage will establish a *status quo* for the waterbody and can be compared to historical data.
>
> (2) Concurrently, a systematic water quality sampling program is established that incorporates a pilot sampling design to determine the space and frequency for measuring the diffuse attenuation coefficient, *K*. The background values and average *K* value are determined from a final sampling plan so that the percent of incident light reaching any depth in the water body can be estimated.

(3) Desirable seagrass coverage goals are established by a management plan. In this step, bathymetric maps of the water body are compared to seagrass depth distributions to determine the *K* values that would be required to achieve the desired coverage.

(4) The *K* values are related to functional water quality parameters (turbidity, chlorophyll, and color) to evaluate which factors are most influential in determining transparency and ultimately, the aerial extent of seagrass coverage.

(5) Once these factors are determined and their sources identified, a plan is implemented to manage the reduction of inputs from the sources considered detrimental to transparency of the waterbody (Kirk, 1988)."

The five-step strategy documented by Kenworthy is related to the fact that *K* is the most important component driving basin management. By manipulating the *K* value and related parameters, scientists may insure that seagrasses will grow to a certain depth. Essentially, a preferred *K* will be developed and used to improve water quality in the basin, based on empirical data.

From this workshop it became clear that the next step in the SAV Initiative was to develop a protocol to measure *K* in the field.

The main goal of the PAR Workshop was to develop a standardized protocol to measure the light that is actually reaching the SAV for use in predictive modeling. In order to reach this goal, the following questions were addressed:

* What should be measured?

* Which is the correct sensor to use to measure the available light?

* What methodology for measuring light can answer questions of:
    * Correction for cloud cover?
    * Stratified water column?
    * Consistent depth profile?

  * Correction for sun angle?
  * Appropriate time-of-day?
  * Required replication?

* How frequently should light be measured?

* What is the best way to calculate attenuation (*K*)?

* How should PAR or *K* be used as a management tool?

There was a strong agreement that light availability is the major factor limiting seagrass growth and survival. Because attenuation of light by the water column is a major factor affecting the available light, the most important factor to measure is water clarity.

Two lines of evidence point to the overwhelming importance of light. Both the physiological basis for responses to light and empirical field relationships of light availability versus maximum depths of seagrass demonstrate that seagrasses require high light levels and that more light results in faster growth rates and more seagrass.

The decision on the most appropriate sensor was highly debated. Although a 2pi sensor may be most appropriate for measuring downwelling radiation, seagrass leaves capture light from all angles. Agreement was reached that a 4pi sensor was most appropriate for measuring the light available for seagrass.

Sampling protocol was extensively discussed. Consensus was reached relating to time-of-day, cloud cover, vertical profile, replication, and calculation of extinction coefficients (*K*). The agreed-to protocol includes: use of a 4π floating, sub-surface reference sensor to correct for cloud cover; a 4π submerged sensor measuring PAR at a vertical profile of: 20, 40, 60, 80, 100 cm, and near bottom; a 4π in-air reference sensor for time-of-day correction; sampling time between 10 a.m. and 2 p.m.; using a 10 sec integration time between depths; measuring three replicate profiles; and *K* calculated as the best fit regression line. The question of required sampling frequency was deferred, pending results from research just starting.

Use of PAR as a management tool could be used to develop a model. The model would need to incorporate incident light, several water quality parameters, epiphytes, and grazers. With the incorporation of depth contours and hydrodynamics, the model could predict acres of seagrass change resulting from management actions.

LITERATURE CITED

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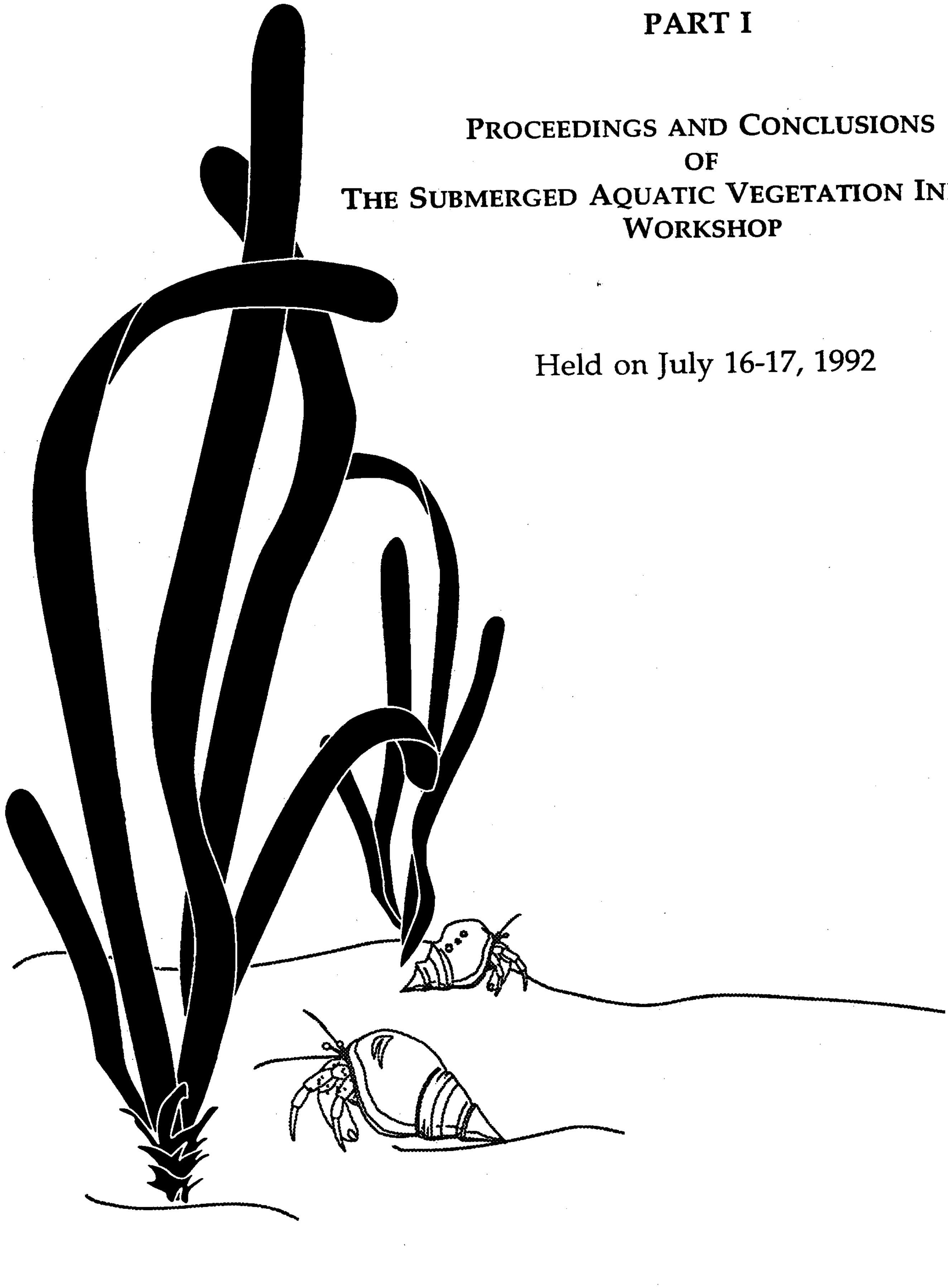
PART I

Proceedings and Conclusions of The Submerged Aquatic Vegetation Initiative Workshop



Held on July 16-17, 1992

SAVI SECTION 1:

INTRODUCTION

THE PURPOSE, ROLE, AND OBJECTIVES OF THE SAVI WORKSHOP

by

Derek Busby, Project Director
Indian River Lagoon National Estuary Program
1900 South Harbor City Boulevard
Suite 109
Melbourne, FL 32901-4749

Derek Busby serves as Project Director for the Indian River Lagoon National Estuary Program. He obtained his M.A. in geography and marine affairs from the University of Rhode Island in 1984 and his B.S. in biology and marine science from Jacksonville University in 1979. His career has been dedicated to coastal resource protection issues in Florida.

The Indian River Lagoon National Estuary Program (IRLNEP) was initiated in April of 1991 shortly after it was designated by the U.S. Environmental Protection Agency as an "estuary of national significance". During the first year, the project focused on identifying major issues for the Indian River Lagoon (IRL) and conducting technical and planning projects related to the development of the project's Comprehensive Conservation and Management Plan (CCMP). A draft Characterization Report summarizing biological, physical and social issues is slated for completion early in 1994. The first draft of the project's CCMP was released in January of 1993.

The Submerged Aquatic Vegetation Initiative (SAVI, which is included in Appendix I) is critical to the Indian River Lagoon. This initiative represents our efforts to protect and restore the most critical habitat component of this diverse estuary; one that is not only important from an ecological standpoint, but perhaps more importantly is recognized as an indicator of the overall health of the system.

The SAVI has a simple goal "to maintain or improve water clarity to a point that submerged aquatic vegetation could increase bottom coverage throughout the lagoon to a depth of two meters". This goal and the concepts outlined within the SAVI are built upon past work both here and in other parts of the country. In the

Indian River Lagoon region the use of submerged vegetation as an indicator of water quality was first explored during a workshop hosted by the South Florida Water Management District in November of 1990. That workshop served to summarize the scientific knowledge regarding light requirements of seagrasses, and examined the potential effects of reduced water transparency upon the survival, distribution and abundance of seagrasses. It also explored the ability of existing water quality standards to protect seagrasses from deteriorating water quality.

From this effort, it was recognized that current water quality standards do not adequately address the needs of seagrasses. Several recommendations were developed including the need to first develop light attenuation standards for seagrasses and then to incorporate those into comprehensive water quality management programs. In the interim, the Surface Water Improvement and Management (SWIM) program and the IRLNEP developed the Submerged Aquatic Vegetation Initiative. That initiative is a simplistic approach to building a link in the public's mind between clean water and a healthy, bountiful estuary.

GOOD WATER QUALITY	=	MORE SEAGRASS	=	MORE ANIMALS,FISH FISHERIES

During July of 1992, the IRLNEP sponsored a follow-up workshop to allow scientists, planners, IRLNEP project staff and various agency personnel to discuss and develop consensus about the SAV Initiative and to explore the means to accomplish the five tasks outlined within the initiative. It was agreed that PAR data, K values and water quality data for certain parameters could be used to calculate "target" concentrations of key "pollutants" affecting water transparency, thereby effectively establishing restoration targets for specific lagoon segments.

Proceedings for the July, 1992 workshop were developed and are incorporated into this publication.

In follow up meetings after the July Workshop it was determined that the methodologies used by the various agencies measuring PAR in the Lagoon were dissimilar. A third workshop to develop a common PAR monitoring protocol was held in January 1993. This common protocol is presently being implemented throughout the lagoon.

Thus a significant evolution has occurred from exploring the available knowledge about seagrasses to developing and agreeing upon the need for PAR monitoring, a standard method for monitoring PAR and developing meaningful, resource-based, water quality targets. All with the purpose of providing an understandable link between good water quality and a healthy resource.

GOOD WATER QUALITY	=	MORE SEAGRASS	=	MORE ANIMALS,FISH FISHERIES

And ultimately with associating good water quality to what occurs in the watershed.

EFFECTIVE WATERSHED MANAGEMENT	=	GOOD WATER QUALITY	=	MORE SEAGRASS	=	MORE ANIMALS,FISH FISHERIES

The following proceedings summarize the current state of knowledge of seagrasses and our ability (or attempts) to determine the conditions needed for their maintenance and improvement. Ultimately, we hope to be able to quantify these conditions and relate them to inputs from the watershed. How that leap is to be made remains a challenge. It is hoped that these proceedings provide at least the initial steps toward meeting that challenge.

INTRODUCTION TO THE SUBMERGED AQUATIC VEGETATION INITIATIVE (SAVI)

by

Daniel Haunert
Senior Environmental Specialist, IRL
South Florida Water Management District
P.O. Box 24680
West Palm Beach, FL 33416-4680

Daniel Haunert is a Senior Environmental Scientist with the South Florida Water Management District. Prior to working for the District for the past 16 years, Mr. Haunert worked for a number of aquaculture companies as a scientist culturing marine and freshwater species. He received his B.A. from Florida Atlantic University in Boca Raton, Florida, in 1973.

The Indian River Lagoon SWIM Program has been geared toward seagrasses in one way or another. I have worked extensively the Dr. Judson Kenworthy on seagrasses and am very familiar with his dissertation work on developing an alternative standard for water quality. Unfortunately Dr. Kenworthy could not be with us during this workshop. However, he has developed a program (see Appendix II) which provides us with the backbone of the SAV Initiative. This program provides information on an alternative to water quality criteria for the monitoring and regulation of water transparency for the protection of seagrasses in the southeastern United States. This document embodies many of the ideas and goals for the SAV Initiative.

We will proceed, taking a closer look at some of the water quality monitoring efforts in the Indian River Lagoon. First, in order to understand seagrasses we must inventory what we have in the field. Seagrass mapping is a very important tool for accomplishing this task. We will have several presentations regarding this subject.

General Strategy of the Layered Approach

by

Robert W. Virnstein, Ph.D.
St. Johns River Water Management District
P.O. Box 1429
Palatka, FL 32178

For the past 5 years, Dr. Virnstein has been the biologist in charge of the Habitats section of the Indian River Lagoon SWIM Program at the St. Johns River Water Management District. Prior to that, he had his own seagrass consulting firm, which he started after working as a research scientist for 10 years at the Harbor Branch Oceanographic Institution.

INTRODUCTION

The main program working in coordination with IRLNEP is the Surface Water Improvement and Management (SWIM) Program. The main goal of SWIM Program for the Indian River Lagoon is:

> "to attain and maintain a functioning **macrophyte-based** ecosystem which supports endangered and threatened species, fisheries and recreation".

This emphasis on a macrophyte-based ecosystem applies directly to the overall goal of this workshop. Our goal here for this workshop is to establish a pathway. This pathway should lead from management actions to improved resources. Here, we need to define the steps along this pathway to a macrophyte-based ecosystem.

These steps are largely defined by the ecological relationships. These relationships can be depicted by a simple model (Figure 1).

Figure 1. A simple model, illustrating the relationship of water quality to seagrass to secondary production.

WATER QUALITY ----> SEAGRASS ----> FISH, FISHERIES

This very simple conceptual model says good water quality results in healthy seagrass and primary production, which results in the production of fish and other animals. It may be a leap of faith to say that if we have seagrass, then we will have fish and fisheries. We do not fully understand which seagrass parameters are the best indicators of a healthy, functioning seagrass system. However, Figure 1 does illustrate how we are using seagrass as a barometer of ecosystem health.

To attain a healthy system, we need to take a layered approach. Each "layer" provides information and guidance at a different level of detail. The layers progress from Lagoon-wide, "big picture" approaches, to identifying conditions in selected areas and then specific sites, and finally identifying specific causes of stress at these sites. Such an approach should include the following:

LAYERED APPROACH

1. Lagoon-wide status & trends
   * aerial mapping, with ground-truthing

2. Status & trends in target areas
   * low-altitude imagery, with extensive ground-truthing

3. Status & trends at selected specific sites
   * fixed, permanent transects, with quantitative monitoring of distribution, abundance, and condition of seagrass

4. Site-specific relationship to water quality parameters
   * water quality versus PAR relationship
   * PAR versus seagrass relationship

These general steps and their uses are described in the following papers. For each of these steps we must force ourselves to ask "so what?" That is, how do we use the information to protect and enhance the Lagoon's seagrass resources?

SAVI SECTION 2:

SEAGRASS MAPPING AND ASSESSMENT

SEAGRASS MAPPING IN THE INDIAN RIVER LAGOON

by

Robert W. Virnstein, Ph.D.
St. Johns River Water Management District
P.O. Box 1429
Palatka, FL 32178

The first "layer" of a layered approach is the Lagoon-wide, "big picture" approach. Lagoon-wide seagrass maps provide this big picture.

What follows is a quick overview of the steps taken to map seagrasses in the Indian River Lagoon and uses of these maps. These maps are the initial step in evaluating the status of seagrass in the Lagoon. Such steps include: aerial photographing; ground-truthing; photo-interpreting and delineating of polygons; registering these to a base map; and digitizing these maps into a geographic information system (GIS).

ELEMENTS OF THE MAPPING EFFORT

1. Aerial photos
   * 9x9 inch, color, infra-red or true-color positives
   * quad scale, 1:24,000 (1 inch = 2,000 ft)
   * winter-spring usually offers greatest water clarity
   * photos every year (proposed)
   * full mapping effort about every 2 to 3 years
     * 1986
     * 1989
     * 1992

2. Ground-truth, using copies or prints of aerial photos
   * spot checks, as needed
   * establish transects
     * permanent, fixed
     * or as needed to interpret

3. Photo-interpret
    * past efforts in 1986 and 1989 -- four density classes
        * <10% coverage
        * 10-40%
        * 40-70%
        * >70%
    * 1992 -- only two classes, narrowed to:
        * dense, continuous beds
        * patchy beds

4. Digitize, plot -- ARC

5. Trend Analysis -- INFO

I emphasize that ground-truthing is an integral and important part of seagrass mapping, as it verifies the interpretation and answers questions raised in the aerial photos. Visual estimates are used in the field.

TRANSECTS AS PART OF THE 1992 MAPPING EFFORT

In addition to simple gross estimates of percent cover to assist photo-interpretation, more rigorous estimates were made along transects starting in 1992. These fixed, permanent transects can then be revisited in subsequent years or seasons.

As part of the 1992 mapping effort, 50 transects were established. These extended roughly perpendicular to shore from the shallowest edge of seagrass out past the deep edge of the seagrass. At a minimum of ten points along the transect, the following parameters were estimated or measured:

* percent cover
* species composition and relative abundance
* algal percent cover
* canopy height
* epiphyte abundance (scale of 0-5)

These parameters enhance the interpretation of Lagoon-wide maps. They provide insight into, or more rigorous indicators of:

* species composition and subsequent changes
* changes along the depth gradient
* separation of signatures of algae versus seagrass
* the correspondence between the densities indicated from the aerial photos and from field measurements

Once the ground-truthing effort has been completed, photo-interpreting, an inexact science, may be completed. As indicated above, four classifications were used in estimating seagrass coverage, from 1986-89. We have now revised our classification scheme to only two categories. Neither of these schemes is perfect. However, we selected the two-category scheme because of the magnitude of the effort, and it appears as if it may be a more repeatable scheme. Once photos are interpreted, we can digitize the maps and continue on to trend analysis.

USES OF LAGOON-WIDE SEAGRASS MAPS

From the point of view of this workshop, the uses of the Lagoon-wide seagrass maps are very important. For example, we can describe large-scale patterns, such as determining how many acres are in a county or segment. We can address trends by county or by segment. If we examine a long stretch of the Lagoon, we see that there is very little seagrass from Cocoa to Grant, compared to most of the rest of the Lagoon.

Appropriate uses of Lagoon-wide maps include:

* To describe large-scale distribution patterns Lagoon-wide, per county, and per segment
    * acres of seagrass
    * percent of bottom with seagrass
* Determine large-scale changes and trends
    * overall
    * per county
    * per segment
* Locate "healthy" and "problem" areas
* Define resource protection areas
* Relate distribution and changes to various water quality parameters
* Relate distribution to bathymetry and distribution goals

Lagoon-wide maps are <u>not</u> suitable for:

* Detecting or describing short-term changes (less than 1 year)
* Detecting localized impacts
* Detecting changes in species composition
* Site-specific permitting
* Detecting small changes in seagrass distribution. Shifts of less than perhaps 10-50 m can not be reliably detected

Certainly, such maps are only representations. As such they can represent only a few selected features. We choose these features based on the details we need. We must realize the limited scale and precision of these maps when we interpret and use them.

The Tampa Bay Experience

by

Thomas F. Ries
Southwest Florida Water Management District, SWIM
Tampa Service Office
7601 U.S. Highway 301
Tampa, FL 33637

Thomas Ries is an environmental scientist with the Southwest Florida Water Management District (SWFWMD), SWIM Program, where he works as project manager on seagrass research projects including mapping and trend analysis. Additional projects include restoration of Tampa Bay estuarine habitats via creation of tidal wetlands and research on the limiting light levels for seagrasses. He received his B.S. in biology with a minor in hydrogeology in 1983 and is currently seeking his M.S. in environmental public health at the University of South Florida.

TREND ANALYSIS IN TAMPA BAY

The SWIM Program is completing seagrass mapping on the west coast of Florida, in Tampa Bay. The program has experienced some problems with mapping and as a result the program has been continually revised.

The SWIM Program of SWFWMD wanted to complete seagrass mapping in the Tampa Bay area since the last time seagrasses had been mapped was by the state Department of Natural Resources in 1982. The intent of the program was to update and document seagrass presence, to determine how the ecological system was progressing in terms of the seagrass trend analysis.

In 1988 the program completed the first mapping effort. We wanted to complete the effort with GIS and ARC/INFO to allow the trend analysis to be more easily completed. To accomplish this we hired Geonix, who have monitored a significant number of mapping projects for the government, namely the National Wetlands Inventory for the U.S. Fish and Wildlife Service.

When we mapped in 1988, true color was used because we hoped to gain better depth penetration with color at 1:24,000, with USGS 7.5 minute quads, taken during the winter months when there is good water clarity, at low tide and low wind. We received good photos, not great, but adequate. In categorizing seagrass coverage, Geonix used three categories, dense, sparse, and patchy.

When we went out in the field to begin our ground-truthing efforts, we realized that the difference between sparse and dense was not what we assumed. Instead, the difference appeared as a characteristic of morphological difference in seagrass species. More specifically, the *Thalassia* spp., with its broad leaves appeared more continuous and dense than other seagrasses (of similar distribution). Consequently, we narrowed the categories to two for the 1988 mapping effort and future mapping efforts. The drawback is that less information was gained on the maps, but the information was correct. Because we gained less information on our maps, we began to define transects.

In 1990, we wanted to update the seagrass maps in a two-year interval to document any changes. We again used true color for the subsequent overflights. Due to the drought in 1990, water clarity was exceptional, thus we were able to attain some very clear maps. During the same time period the District was mapping land features using color/IR photography at the same scale. By comparing the overlap area we have concluded that true color has superior light penetration, which made it easier to distinguish species. In fact, the 1990 water clarity was so good that we were able to pull out *Caulerpa* spp. (attached algae areas), as defined as a separate signature from SAV.

Due to less information gained overall, we established transects (starting in 1990). Seventy transects were located throughout Tampa Bay. These transects were 1,000 meters long with data points every 100 meters. We collected information on species presence, blade width of species, epiphyte loading, bottom characteristics-hard bottom/soft bottom determination, depth of the water and relative abundance of algae.

Lewis *et al.* (1983) suggested we have had an 80 percent seagrass loss in Tampa Bay since the 1800s. Obviously, we hoped to reverse that trend and we needed to identify what kind of trend in seagrass coverage was occurring.

In 1990, we completed a trend analysis of the entire mapping area for all of Tampa Bay (Table 1). The results are significant and include the percent change

TABLE 1
Total Acreage of Seagrass Beds in the Tampa Bay Area

BOTTOM TYPE	1988 ACRES	1990 ACRES	CHANGE	
			ACRES	PERCENT
Seagrass, Continuous	18577	20182	1605	8.64
Seagrass, Patchy	10040	10750	709	7.06
Attached Algae	0	633	—	—
Seagrass and Algae(Total)	28617	31565	2948	10.3
Tidal Flats /Submerged Shallow Platforms	25097	23699	-1397	-5.57
Beaches	97	881	-10	-10.30
Estuaries, Bay and Gulf	338381	336800	-1581	-0.46
Land	366970	367009	39	0.01
TOTAL	759162	759162	0	0

in acres of seagrass: 1605 in continuous and 709 in patchy.

These numbers represent acres of seagrass percent change in the positive direction for that category. With a closer look, the percent changes offer a better insight into the increases in seagrass coverage.

Table 2 gives an even greater understanding of seagrass increase. Of the 1605 acres, 75 percent was derived from the category of patchy grass beds which grew into continuous coverage. We expected this observation for expanding and healthy seagrass areas. We concluded, that a 27 percent increase of seagrass areas originated from bare bottom. As a result, the 709 acres in Table 1 represents a significant number of brand new seagrasses in Tampa Bay within a two year period.

Part of this mapping effort was to determine whether the efforts of the SWIM department and other programs are making headway with improving water quality in Tampa Bay. The results seem to indicate that they are effective programs. I must preface these remarks with the fact that we had a significant drought in 1990 and less surface water was entering the Bay thus potentially increasing water clarity.

At this point we need to repeat the mapping to see if this trend is real and will continue through 1992. Also we plan to revisit all our transects on an annual basis to develop site specific information to gauge species changes as an early indicator of the health of the system.

TABLE 2
Cross Tabulation of Seagrass Change Categories Between 1988 and 1990 in Acres

1988	Seagrass continuous	Seagrass patchy	Attached algae	Beaches	Tidal flats/algae submerged shallow platforms	Estuaries Bay and Gulf	Land	TOTAL
1990 Seagrass continuous	—	2030	0	0	599	244	0	20181
Seagrass patchy	876	—	0	0	1656	991	0	10750
Attached algae	0	0	—	0	632	1	0	633
Beaches	0	0	0	—	23	2	5	88
Tidal flats/submerged shallow platforms	309	647	0	14	—	789	23	23699
Estuaries Bay and Gulf	92	127	0	3	243	—	19	336801
Land	1	0	0	22	36	28	—	367099
TOTAL	18577	10040	0	97	25097	338381	366969	

This is how the program has evolved. We have been lucky to have the same person completing the photo-interpreting over the years. It is very important to enter the field to conduct your initial ground-truthing as soon as possible after shooting the photos.

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ASSESSMENT OF SEAGRASS HABITATS AND WATER QUALITY IN SARASOTA BAY

by

David A. Tomasko, Ph.D.
Sarasota Bay National Estuary Program
1550 Ken Thompson Highway
Sarasota, FL 34236

Dr. Dave Tomasko received his Ph.D. in biology from the University of South Florida (USF) in 1989. His dissertation research, carried out under the guidance of Dr. Clinton Dawes, centered on the analysis of clonal growth properties of seagrasses. After finishing his degree at USF, Dr. Tomasko took a year post-doctoral position at the University of Texas Marine Science Institute in Port Aransas, TX. Studies there focused on the light requirements of seagrasses. After Texas, Dave took a position with the Florida Keys Land and Sea Trust and researched the effects of nutrient pollution from septic tanks on seagrasses of the Florida Keys. Since April of 1991, Dave has worked with the Sarasota Bay National Estuary Program as a senior scientist. The Sarasota Bay NEP has spent nearly $3 million over the past few years on a technical diagnosis of Sarasota Bay. In the fall of 1992, a report on bay problems and a preliminary list of management options was released to the public through the program's "Framework of Action".

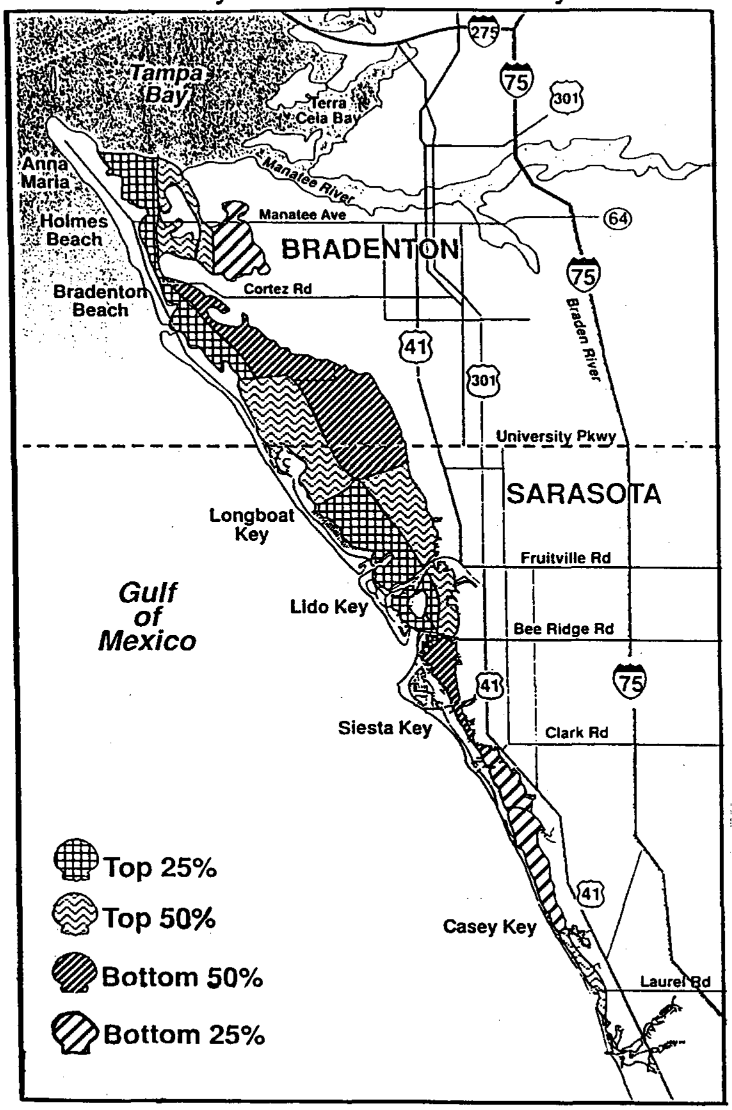
OVERVIEW

The Sarasota Bay National Estuary Program (SBNEP) has utilized a nutrient loading model and an analysis of status and trends in water quality to provide useful information for managing seagrasses and other habitats within Sarasota Bay. Detailed information on water quality, nutrient loading, seagrass distribution, and fisheries status is available in the "Sarasota Bay National Estuary Program Framework of Action", published by the SBNEP.

Sarasota Bay is not a priority water body under the Surface Water Improvement and Management Program (SWIM). The Florida Department of Natural Resources has studied water quality, habitat trends, and fisheries status in Tampa Bay and Charlotte Harbor, but little work has focused on Sarasota Bay. Consequently, past characterization and monitoring efforts in Sarasota Bay have been based on local efforts, with a limited pool of available funds. Extensive historical data bases, as in Tampa Bay, simply do not exist.

Sarasota Bay, like other parts of Southwest Florida, experiences distinct wet and dry seasons. Approximately 60 percent of the Bay's rainfall occurs during a 5 month period, from June to October (Heyl, 1992). Associated with this seasonality in rainfall, water quality changes dramatically at any given point in the Bay, dependent upon the time of the year (Lowrey, 1992). Therefore, it is important that monitoring programs do not confound seasonal differences in water quality with spatial differences when assessing the relationships that exist between water quality and seagrass distribution.

Figure 1. Relative water clarity index for Sarasota Bay



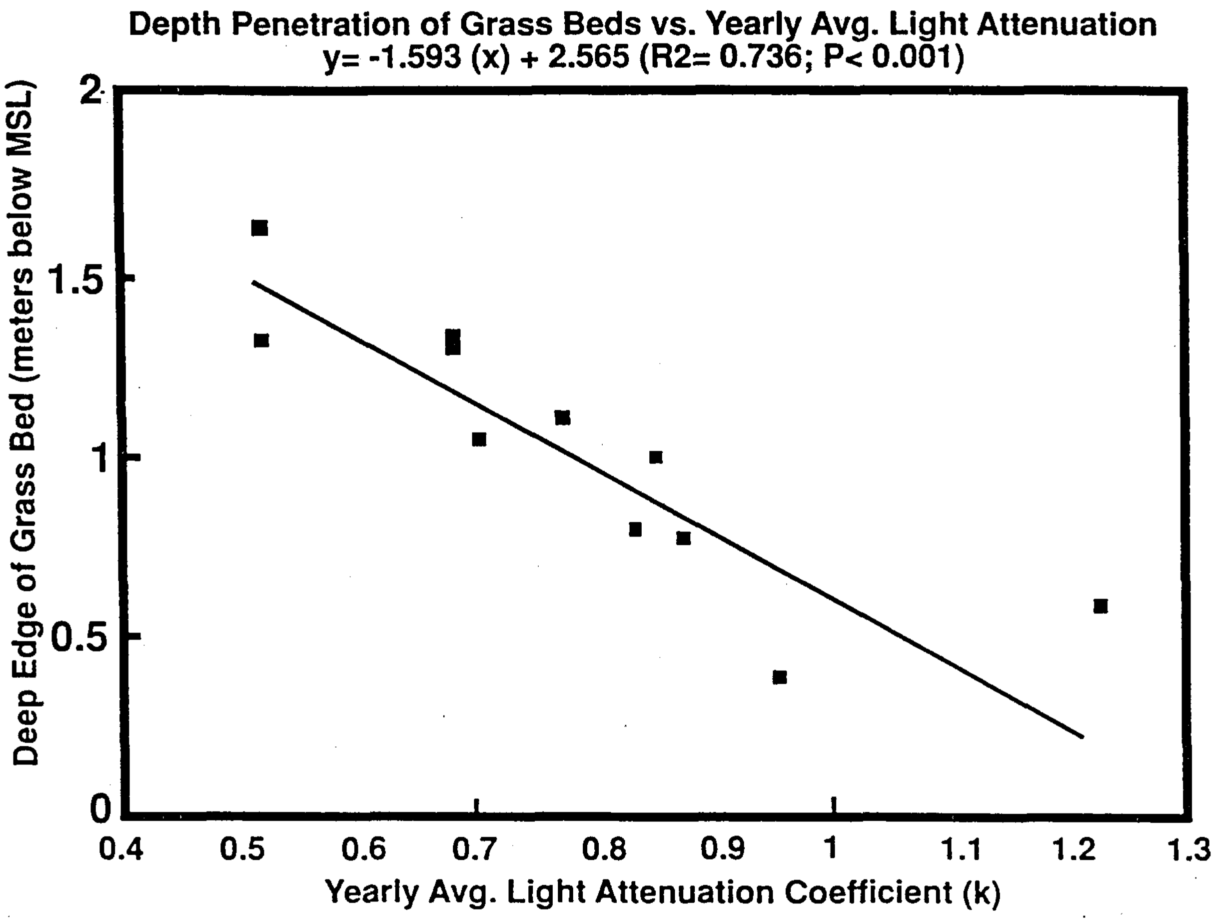
IMPORTANCE OF WATER CLARITY AND VARIOUS LIGHT ATTENUATORS

As can be seen in Figure 1, water clarity in Sarasota Bay varies spatially. Some of the difference in water clarity is attributed to differences in circulation and flushing. Areas closest to passes generally have the best water clarity, and areas in null zones for circulation typically have reduced water clarity. However, exceptions do exist. Roberts Bay, the area just east of Siesta Key, is in the bottom 50 percent of all Bay segments for water clarity, yet it is in the upper 33 percent of all Bay segments in terms of flushing rate (Sheng and Peene, 1992). Also, the area just east of central Longboat Key, which is in the top 50 percent of all Bay segments for water clarity, is in the lower 33 percent of all Bay segments in terms of flushing rate, being located in the null zone between New Pass and Longboat Pass (Sheng and Peene, 1992).

A potential reason for the lack of water clarity in Roberts Bay, despite its thorough flushing, is that Roberts Bay receives the discharge of Phillippi Creek. Phillippi Creek has the largest watershed of any tributary to Sarasota Bay, which contains the majority of the 45,000 septic tanks located in the Sarasota County portion of the Bay watershed (Heyl, 1992). The combination of stormwater and wastewater loads seems to be associated with the elevated Chlorophyll *a* levels found in Roberts Bay (Lowrey, 1992). In contrast, the area east of Longboat Key has no wastewater discharges to the Bay, and the reduced land area is associated with low levels of stormwater runoff (Heyl, 1992).

In order to document that the water quality monitoring program in Sarasota Bay has biological relevance, an attempt was made at correlating the depth to which seagrasses grow in any particular segment to the yearly average light attenuation coefficient for all non-tributary stations within that segment. The results, Figure 2, suggest that the current method of measuring water clarity is a meaningful tool for estimating the depth to which seagrasses can grow in Sarasota Bay. With the shallow bottom slope in Sarasota Bay, dramatic increases in seagrass habitat can be achieved with minimal increases in water clarity. For example, if seagrasses could grow to one more foot of water depth in Little Sarasota Bay (which would require average K values going from 1.26 to 1.07), it is estimated that the amount of seagrass habitat in this area could potentially go from the present 647 acres (Culter, 1992) to a projected total of 1,434 acres (Tomasko *et al.*, 1992).

Figure 2. Depth limits of seagrasses in Sarasota Bay as a function of segment-wide annual average light attenuation coefficients.



However useful it might be to have a relationship between measures of water clarity and the extent of seagrass habitat, such information is of limited use to resource managers. Although it is beneficial to seagrasses and the organisms dependent on them to increase water clarity, the question arises as to how increased water clarity might be brought about. Preliminary data suggest that water clarity in Little Sarasota Bay and Palma Sola Bay is strongly affected by the abundance of dissolved substances ("color"), while water clarity in Roberts Bay seems to be most strongly affected by the abundance of phytoplankton populations, which are themselves limited by the availability of nitrogen (Tomasko *et al.*, 1992; Tomasko, unpubl. data).

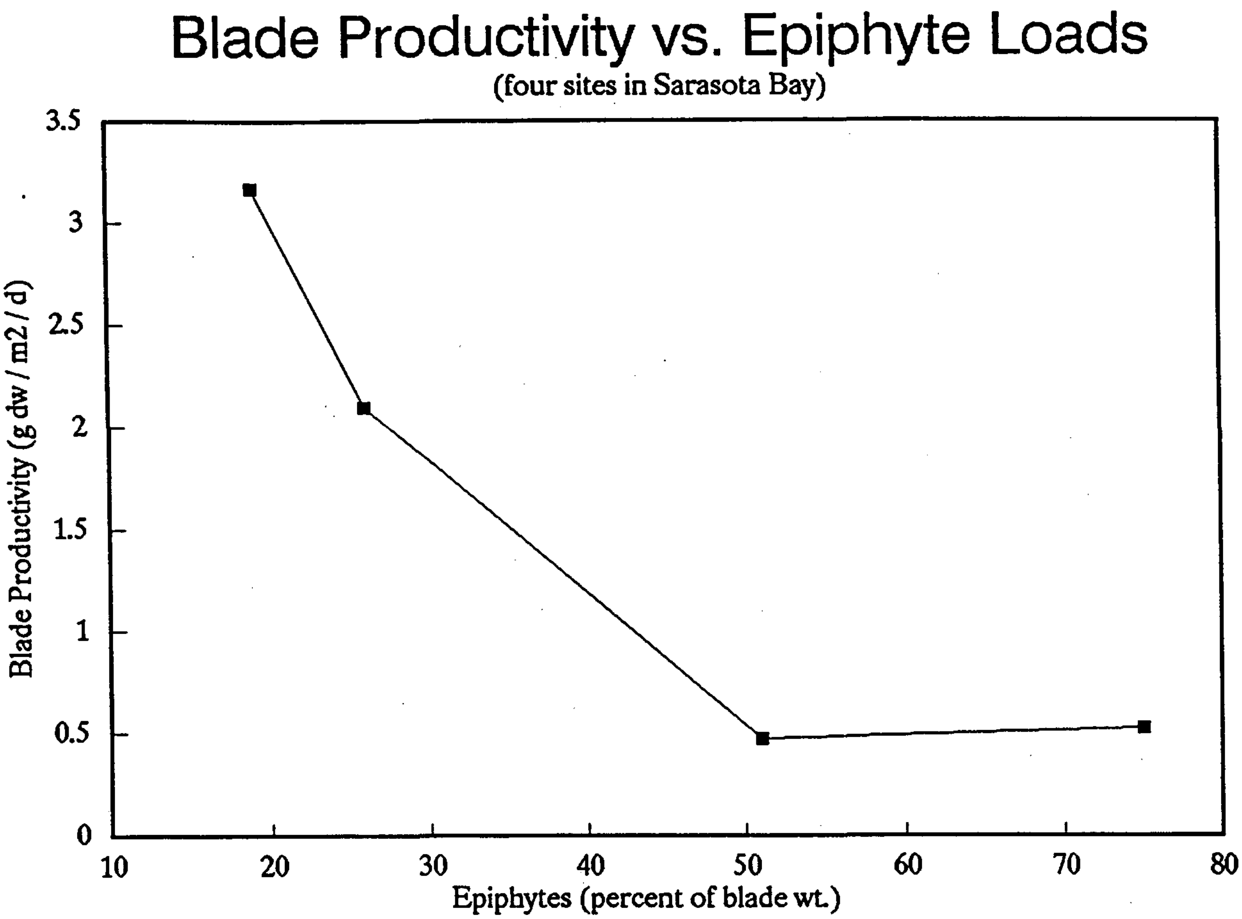
To further aid resource managers in making the appropriate kinds of decisions to increase water clarity, SBNEP is currently funding a project similar to that used in Charlotte Harbor by McPherson and Miller (1987) to determine the relative importance of various light attenuators. With this information, informed decisions can be made regarding the appropriateness of various activities aimed at increasing water clarity.

IMPORTANCE OF EPIPHYTE LOADS

An additional factor to consider when managing water quality for seagrass habitats is the level of epiphyte coverage on the blades of the seagrasses. Previous work in Australia (Silberstein *et al.*, 1986; Neverauskas, 1987), Texas (Dunton, 1990), Denmark (Borum, 1985), and Florida (Tomasko and Lapointe, 1991; Lapointe *et al.*, in press) has illustrated the relationship between increased water column nutrient loads, increased epiphyte abundances, and decreased seagrass productivity and biomass. The primary mechanism reducing seagrass productivity with increased epiphytism is reduced irradiance at the blade level. Shading by epiphytes can reduce irradiance by up to 70 percent (Sand-Jensen, 1977; Silberstein *et al.*, 1986).

Preliminary work in Sarasota Bay (Figure 3) concurs with these other studies, with increased epiphyte abundances being correlated with decreased areal blade productivity. Using the relationship between epiphyte abundance and light reduction determined for *Thalassia testudinum* by Odum (1985), it is estimated that the heaviest epiphyte loads in Sarasota Bay are capable of reducing available light by approximately 32 percent (Tomasko, unpubl. data). As epiphyte abundance increases with increased nutrient loading of the water column

Figure 3. Areal blade productivity of *Thalassia testudinum* versus blade epiphyte loads.



(Dunton, 1990; Tomasko and Lapointe, 1991; Lapointe *et al.*, in press), it is no surprise that the seagrasses with the highest epiphyte levels in Sarasota Bay come from Roberts Bay, which has the highest nutrient loads of any segment of Sarasota Bay (Heyl, 1992).

IMPORTANCE OF RECURRENT HYPOXIA

Despite increased awareness of the importance of seagrasses, most of this concern is centered around the animal usage of these habitats. Therefore, information on the faunal component of seagrass habitats is extremely important. Preliminary studies by SBNEP have recorded recurrent hypoxia (D.O. < 2 ppm) in parts of Sarasota Bay (Figure 4). Despite the importance of D.O. in maintaining healthy animal communities, little information has been collected to accurately measure the degree of hypoxia that can occur in nearshore systems. In Figure 5, which is a rearrangement of the same data in Figure 4, the relation between D.O. and hours after sunrise becomes apparent. As most monitoring programs rely on daytime sampling (water clarity measurements require the sun to be nearly overhead), pre-dawn D.O. sags are not adequately captured.

A SBNEP study by Leverone and Marshall (1992) examined differences in animal communities in seagrass beds of varying status. "Pristine" and "impacted" meadows of both turtle grass (*Thalassia testudinum*) and shoal grass (*Halodule wrightii*) were studied to determine differences in the numbers of fish, shrimp, and crabs between these categories of seagrass meadows (8 sites were used). Elevated abundances of macroalgae and pre-dawn D.O. sags were parameters used to classify a site as impacted. No significant difference could be found between animal communities found in pristine and impacted turtle grass beds. However, impacted shoal grass beds contained far fewer carridean shrimp compared to their pristine counterparts.

Leverone and Marshall (1992) concluded that if water quality degraded to the point that animals were excluded due to recurrent hypoxia, turtle grass would be excluded as well. However, shoal grass could survive in areas of water quality bad enough to kill off particularly vulnerable species, such as carridean shrimp. It appears that turtle grass might be useful as a bio-indicator of good water quality, as it is often replaced by shoal grass in areas of increased nutrient loading (Reyes and Merino, 1991; Tomasko *et al.*, 1992; Lapointe *et al.*, in press).

Figure 4. Dissolved oxygen levels (mg / l) over a seven day period in Little Sarasota Bay.

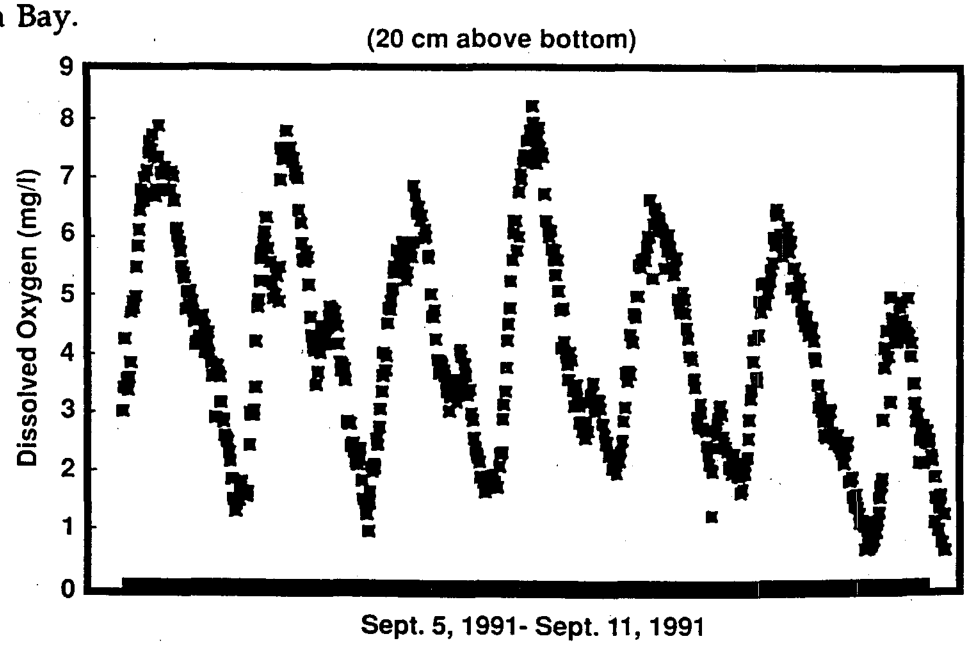
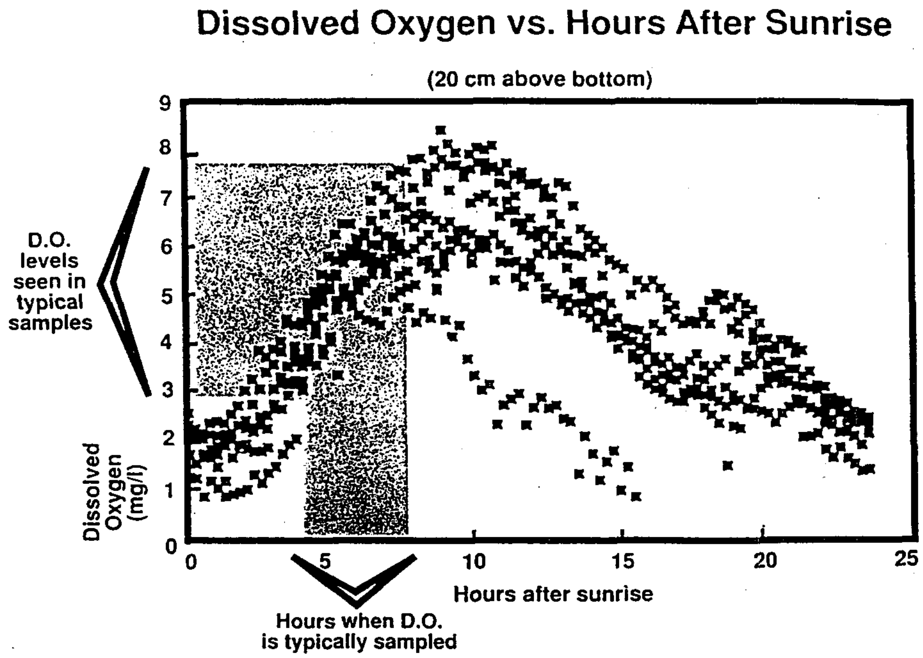


Figure 5. Dissolved oxygen levels (mg / l) versus hours after sunrise. Data are rearranged from Figure 4.



CONCLUSIONS

Through the documentation of the relationship between water clarity and the depth to which seagrasses can grow, it is now possible in Sarasota Bay to predict increases or decreases in seagrass habitat associated with changes in water clarity.

In addition, a study is underway to determine which light attenuators are most important in reducing underwater light, as well as what role epiphyte abundance plays in light attenuation at the blade level. Also, the relationship between nutrient enrichment of the water column, increased epiphyte loads, and decreased seagrass productivity has been documented. This information can be used to depict the benefits expected with implementation of a nutrient load reduction strategy.

Additionally, the relationship between increased abundance of macroalgae, recurrent hypoxia, and a depauperate seagrass fauna has been documented. Several points are then clear as regards the animal usage of seagrass beds: 1) turtle grass seems to be an indicator of good water quality, 2) shoal grass can persist in areas of reduced water quality where specific animals can be excluded, and 3) the limitation of seagrass habitat mapping is that presence does not necessarily equal function.

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THE FLORIDA STATE-WIDE DISTRIBUTION AND ABUNDANCE

by

Margaret O. Hall, Ph.D
Florida Department of Environmental Protection
FL Marine Research Institute
100 Eighth Ave, SE
St. Petersburg, FL 33701-5095

Dr. Margaret Hall is an Associate Research Scientist with the Florida Department of Environmental Protection, Florida Marine Research Institute in St. Petersburg. Dr. Hall is an estuarine ecologist, with primary interest in seagrass ecosystems. Her recent and on-going research topics include physical impacts to seagrass beds (e.g. reduced light, prop scars), faunal community structure in natural versus restored seagrass systems, influence of drift algae on seagrass fauna, and structural and functional differences in seagrass communities with respect to hydrodynamic energy regime. She is also involved in a study to investigate the genetic and clonal structure of *Spartina alterniflora* populations in Florida.

SEAGRASS MAPPING

The Florida Marine Research Institute (FMRI) currently has a state-wide database for seagrass distribution and abundance. However, the data for some areas are better than for other areas because the quality of aerial photography varies between locations, and much of the information is dated. For some parts of Florida, the most recent data are from the late 1970s or early 1980s. One of the main goals of the Marine Resources GIS program is to continually update this state-wide seagrass database as new aerial photography becomes available. For example, the seagrass maps being generated for the Indian River Lagoon, Tampa Bay, and Sarasota Bay by SWIM and NEP will be used to update the FMRI state-wide database. All seagrass mapping data are in ARC/INFO.

FMRI is also involved in several other projects where seagrass maps are being updated. The first is a cooperative effort between NOAA and FMRI. The goal of this project is to map benthic resources from the Florida Keys to the Dry Tortugas for the Florida Keys National Marine Sanctuary. Not only seagrasses, but also corals, hard bottom areas, and patch reefs will be mapped. These data will update information we currently have in our database for this region, which was collected in the late 1970s.

All the aerials for the Florida Keys, (and also for Biscayne Bay and Florida Bay) were flown with ground control points and GPS information during 1991-1992 at 1:48,000 with natural color film. This type of controlled photography permits the use of a new mapping tool called the analytical stereo plotter. The numerous ground control points allow for aerotriangulation by the stereo-plotter. After aerotriangulation is complete, the compiler can interpret and digitize the aerial photography, thus eliminating some steps of the traditional mapping method. The positional accuracy is also better than that obtained with traditional mapping techniques. The digital information is then converted into an appropriate GIS program, such as ARC/INFO.

FMRI would also like to update their existing 1987 database for Florida Bay. We have good quality, recent aerial photography for Florida Bay. However, there is no money available for compilation costs. FMRI is presently seeking funding for this project. We feel that it is extremely important to monitor the Florida Bay seagrass beds, because they comprise such a large portion of Florida's seagrass resource, and also because of the seagrass die-back which occurred in Florida Bay since the 1987 photography was flown.

The Biscayne Bay Benthic Mapping Project is an ongoing effort between FMRI, DERM, and SFWMD's SWIM Program. A number of benthic resources including seagrasses will be mapped. In addition, water quality data from a number of stations throughout Biscayne Bay will be integrated into the final resource map and GIS database.

FMRI is working with the EPA EMAP Program, USFWS, NOAA, and the other Gulf states to map the seagrasses from Tarpon Springs to Mexico. FMRI will provide ground-truthing and coordination in the mapping effort in exchange for the resultant digital maps.

SPECIFIC LOCATION PROP-SCAR MAPPING

The purpose of this project is to assess extent and location of prop-scar damage on a state-wide basis. To accomplish this project, aerial surveys will be flown at 1,000 feet. The observer in the plane who delineates the damaged areas will have a nautical chart (1:40,000), or preferably aerial photography and a nautical chart to determine location of the prop-scars. It is much easier to pinpoint location when both aerials and nautical charts are available.

Seagrass areas damaged by prop-scars will be outlined on the charts and aerials with polygons by the observer. Polygons will vary in size depending on how large the damaged areas are, but polygons will not be any smaller than one acre. The level of damage in the polygons will also be ranked. Currently, there are three categories of damage: low, moderate, and severe. Prop-scar damage was ranked subjectively for Tampa Bay, but the investigators are now developing a sampling grid which will enable them to quantitatively determine the level of damage. Observers are also videotaping the grass beds to document the various levels of damage. The information on the charts will be digitized into the FMRI's GIS database. There will also be some ground-truthing to verify data collected during overflights. The prop-scar assessment project was begun this June, so the techniques are still being refined. Only Tampa Bay has been completed at this time, but when the study is concluded the report will include state-wide acreage of prop-scar damage and a summary by county.

The mapping project described above will provide general information concerning prop-scar damage to an area, but sometimes more accurate information concerning the level of prop-scar damage in a particular seagrass bed might be required. For example, precise estimates of prop-scar damage may be necessary to get permission to close an area to motorized vessels, or perhaps to monitor recovery from prop-scar damage in a seagrass bed. FMRI recently conducted a study at Weedon Island State Preserve in Tampa Bay to identify the precision of prop-scar damage assessment using aerial photography flown at three different scales including 1:24,000, 1:12,000 and 1:2,400. Precision was assessed by evaluating the amount of information gained or lost between scales. Seven hundred individual prop-scars were delineated using color aerial photography flown at 1:2,400, 104 scars were visible at 1:12,000, and only 5 scars could be detected at 1:24,000. The 1:24,000 aerials were hazy, however, by using aerials from another source flown at the same scale, 78 scars could be identified. This was almost as many prop-scars as were visible at 1:12,000. The investigators concluded that it was possible to assess prop-scar damage at all scales, but information was much more accurate at a larger scale. However, both time and money increase with scale. For example, it takes 20 times as long to interpret the 1:2,400 aerials as the 1:24,000 aerials. Comparatively, there are 46 photos for the 1:2,400 scale and only one photo for 1:24,000. Thus, the scale an investigator decides to use to assess damage ultimately depends on the goals and money available for the project.

CHESAPEAKE BAY SAV MONITORING PROGRAM

by

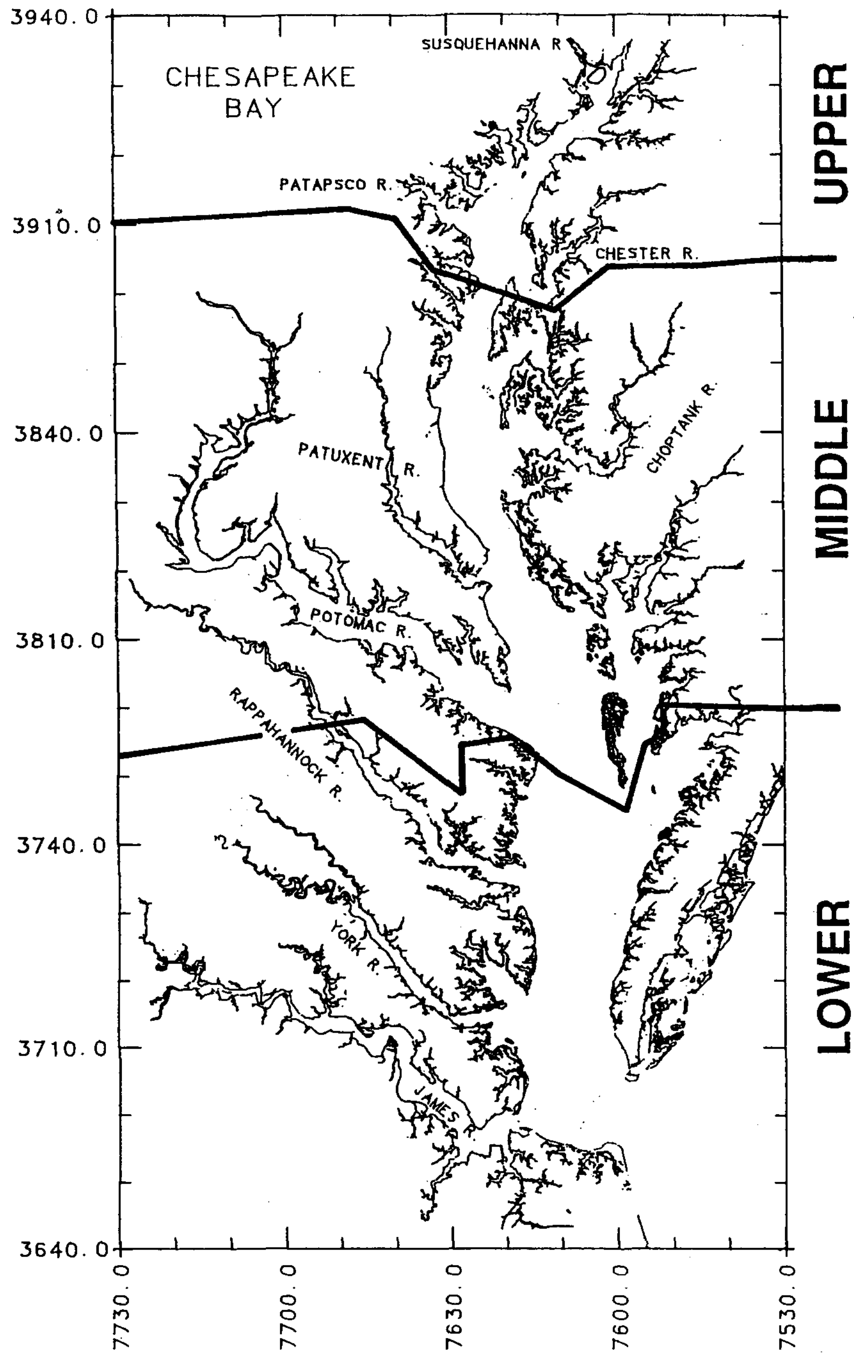
Robert J. Orth, Ph.D
School of Marine Science
Virginia Institute of Marine Science, College of William and Mary
Gloucester Point, VA 23062

Dr. Robert Orth is an Associate Professor at the Virginia Institute of Marine Science and the School of Marine Science at the College of William and Mary in Williamsburg, VA. He currently serves as Chair of the Department of Biological Sciences. He received a B.A. in biology from Rutgers University, a M.S. in marine biology in 1971 from the University if Virginia and a Ph.D. in zoology from the University of Maryland in 1975. Dr. Orth has been actively involved in research on seagrasses of the Chesapeake Bay since 1969. His research is related to distribution and abundance, role and value, and transplanting to enhance areas currently devoid of SAV. Dr. Orth has published numerous articles in scientific journals, as well as grant reports, in the areas of research listed above.

I would like to share some of the results of our research on Submerged Aquatic Vegetation (SAV) in Chesapeake Bay. Increased awareness of SAV in the Chesapeake Bay over the past two decades was a result of the unprecedented and dramatic decline of all species in the early 1970's. The decline was Bay-wide, unlike in the past, where declines affected one species in local areas.

An ambitious SAV program in the late 1970's and early 1980's was aimed at understanding the role and value of SAV, the causes for the decline and examine the current and past status of SAV. The 1980's were highlighted by a flurry of committee work, similar to what we have here today, to try to develop management policies for the different resources, including SAV in the Chesapeake Bay. From that committee, we developed a Submerged Aquatic Vegetation Management Policy, which was signed by the governors of all the states surrounding the Bay. This highlighted areas of restoration, protection, monitoring, and education (see Appendix III). This was a very critical document, because it highlighted how important SAV was to the Chesapeake Bay. Coupled

Figure 1. Map of Chesapeake Bay and tributaries with Upper, Middle, and Lower zones and locations of all SAV beds in 1990. (Latitude and Longitude are in decimal degrees along the vertical and horizontal axes, respectively.)



with the Management policy was an Implementation Plan, which puts into affect the SAV policies.

An important component of the SAV Management Policy was monitoring SAV Bay-wide using aerial photography. An annual program using aerial photography was instituted in 1984 (following the first bay-wide survey in 1978), and continues today. This program is funded through a cooperative effort by state and federal agencies.

The monitoring program uses standard protocols developed during the program. These protocols are being incorporated into a national seagrass status and trends program supported by NOAA. The monitoring program annually produces 1:24,000 scale maps depicting all SAV beds. Figure 1 is a composite of all quadrangles having SAV in the Bay. The data are stored in a GIS system (ARC/INFO) which allows retrieval of data at any scale. It also allows the comparison of data between years, as well as the development of composite beds for any area based on the distribution of SAV in that area across years.

THE TIERED APPROACH

The SAV distribution data will be used in assessing the success of the clean-up of the Chesapeake Bay. Restoration targets have been set for SAV in three tiers, each tier representing increasing abundances of SAV with improving water quality in the Bay as managers and regulators begin to deal with both point and non-point sources of pollution (Figure 2).

Table 1 shows the target abundances for the three tiers and the 1990 distribution data as a percentage of each target (Tier II target has not been fully implemented as the one meter contour for the bay and tributaries has not been completely digitized). From this, we are at roughly 50 percent of Tier I and 10 percent of Tier III. These are baseline numbers that will provide managers a quantitative measure of improving conditions in water quality in the Bay.

The SAV program in the Chesapeake Bay has been an unequivocal success because of the efforts of scientists, citizens, managers and politicians working in a cooperative fashion to insure a clean, healthy Bay for the living resources of the Bay, and for the future generations of people who will be the beneficiaries of our efforts.

Figure 2. Chesapeake Bay SAV Distribution Restoration Targets Setting Process.

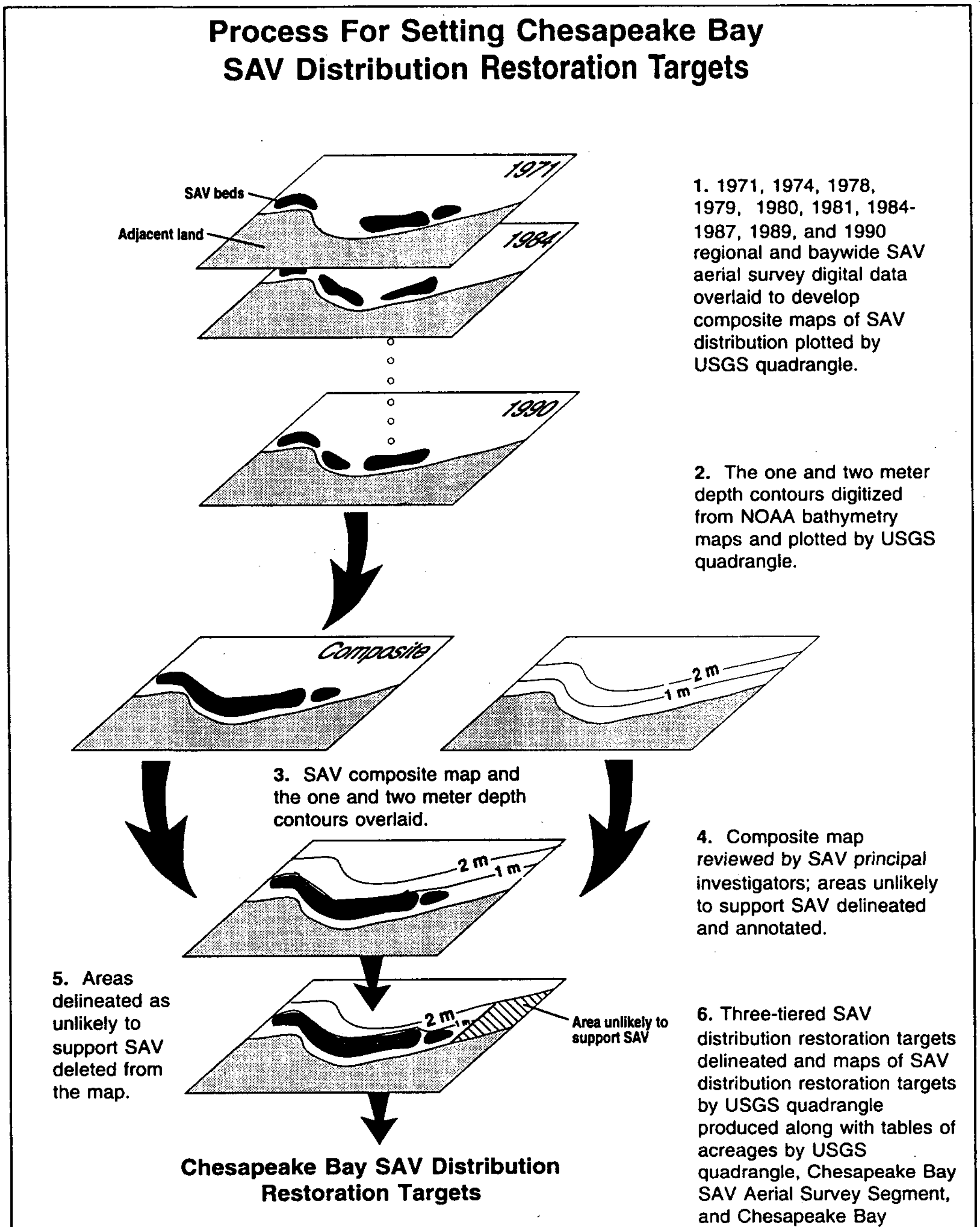


Figure VI-1. Process for setting Chesapeake Bay SAV distribution restoration targets.

Table 1. Chesapeake Bay SAV Distribution Restoration Targets and 1990 SAV Distribution. The percentage in parenthesis beside each target is the 1991 SAV distribution as a percentage of that SAV distribution restoration goal. Efforts to quantify areas covered under the Tier II Target were in process at the time of publication.

1990 SAV Distribution	Tier I Target	Tier II Target	Tier III Target
24,296	47,382 (51.5%)	in process	250,824 (9.7%)

SAVI SECTION 3:

SITE-SPECIFIC SEAGRASS MONITORING

PERMANENT, FIXED TRANSECTS

by

Robert W. Virnstein, Ph.D.
St. Johns River Water Management District
P.O. Box 1429
Palatka, FL 32178

Permanent, fixed transects can be used as a tool for identifying change at a smaller scale of space and time than Lagoon-wide maps. Lagoon-wide mapping done every 2-3 years is most useful for detecting large-scale changes over time periods of at least a year.

For detecting small-scale changes, permanent, fixed transects might be the best tool. Fixed transects eliminate spatial variability, which could mask temporal changes when sampling in patchy seagrass beds. However, by increasing temporal precision, spatial resolution is lost. Change can thus be detected only along a particular transect or at a particular spot along the transect. But many transects within an area would increase the power of inference within that area.

Permanent transects can offer a precise reference of what is present in a given location at a particular time. For example, suppose a storm or major rain event occurs, and we wish to detect whether this event impacted the seagrasses. We cannot depend on Lagoon-wide maps to determine small changes, such as loss of patches less than one acre, or shifts in the edge of a seagrass bed by a few tens of meters or changes occurring within a few months. As a result, we have to wait at least another year to determine whether changes occurred, and thus are unable to attribute changes in seagrass to particular events. If permanent transects had been sampled previously in the area and an event occurs, we can return to the same transect and determine if any changes have occurred since the previous sampling. We cannot determine any change in a system without taking into account natural variability and repeatedly sampling the same location.

SWIM is starting this transect work in 1993, initially in the Sebastian area. Plans are to have at least 50 permanent transects throughout the Lagoon that would be sampled at least twice a year -- summer and winter.

Parameters visually estimated or measured along the transects as part of the Lagoon-wide mapping effort include:

* seagrass percent cover
* species composition and percent cover of each species
* canopy height
* algae percent cover
* epiphyte abundance (scale of 0-5)

The permanent transect monitoring includes shoot counts. Estimates or measurements are made every 10 m.

A large part of the initial effort toward implementing these permanent transects is developing the methodology to sample (1) repeatedly along the same line and at the same spots along the line, (2) non-destructively, and (3) rapidly. Permanent status is achieved by marking the transects with a series of stakes driven into the sediment. A measured tape taughtly strung between the stakes exactly marks the line. Sampling occurs every 10 m along the line.

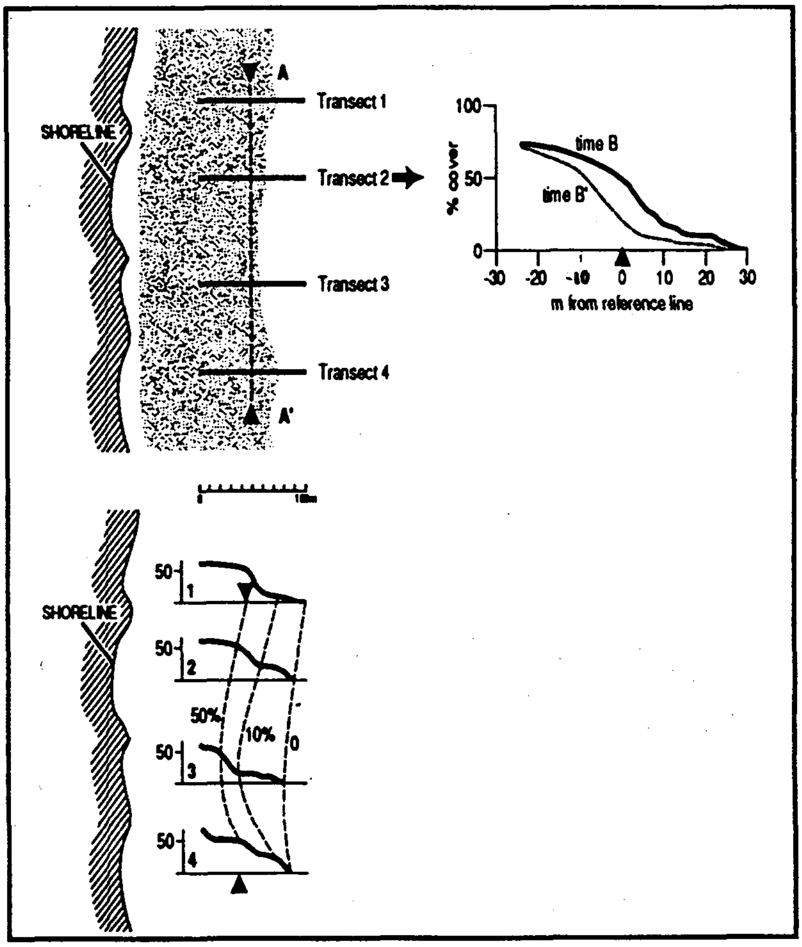
Developing non-destructive rapid techniques has been difficult and is ongoing. Two general approaches are being pursued. One effort is to develop visual estimates of seagrass and epiphyte biomass. To be meaningful, these visual estimates must correspond to quantitative estimates. We are in the initial stages of developing these visual estimates. Such technique development requires taking many samples and measurements over a range of densities to measure the precision and accuracy of the corresponding visual estimates. A photo-reference guide is being developed for matching with field densities.

The second effort is directed toward developing techniques using underwater video. The potential of this method is to serve as the device for collecting the data, the information can be recorded rapidly and inexpensively on tape, and it provides a permanent archival record of the distribution and condition of the seagrass along the transect line.

USES OF PERMANENT, FIXED TRANSECTS

There are two ways to use these transects. A single transect could be used as a unit of measure. We could look at that same transect over and over to gain detail about a particular bed. We could also have several transects across a single bed as in Figure 1. These transects could be sampled at time B and again at time B'.

Figure 1. Illustrating the use of several transects to define the outer edge of a grassbed.



These several transects could be used to define the contour, e.g. of 10% cover or 50% cover to define changes in the "edge" of the grassbed (Figure 1). Thus, we could use either a single transect or several transects to describe an area.

In summary, permanent, fixed transects can:

1. Aid interpretation of:
   * aerial photos
   * seagrass maps
   * impacts of changes in water quality

2. Detect site-specific changes over time, by:
   * detecting declining areas
   * documenting improvements
   * detecting changes other than simple abundance or presence/absence
     * growth
     * species composition
     * abundance -- percent cover, shoot density
     * canopy height
     * condition

TAMPA BAY SEAGRASS MAPPING

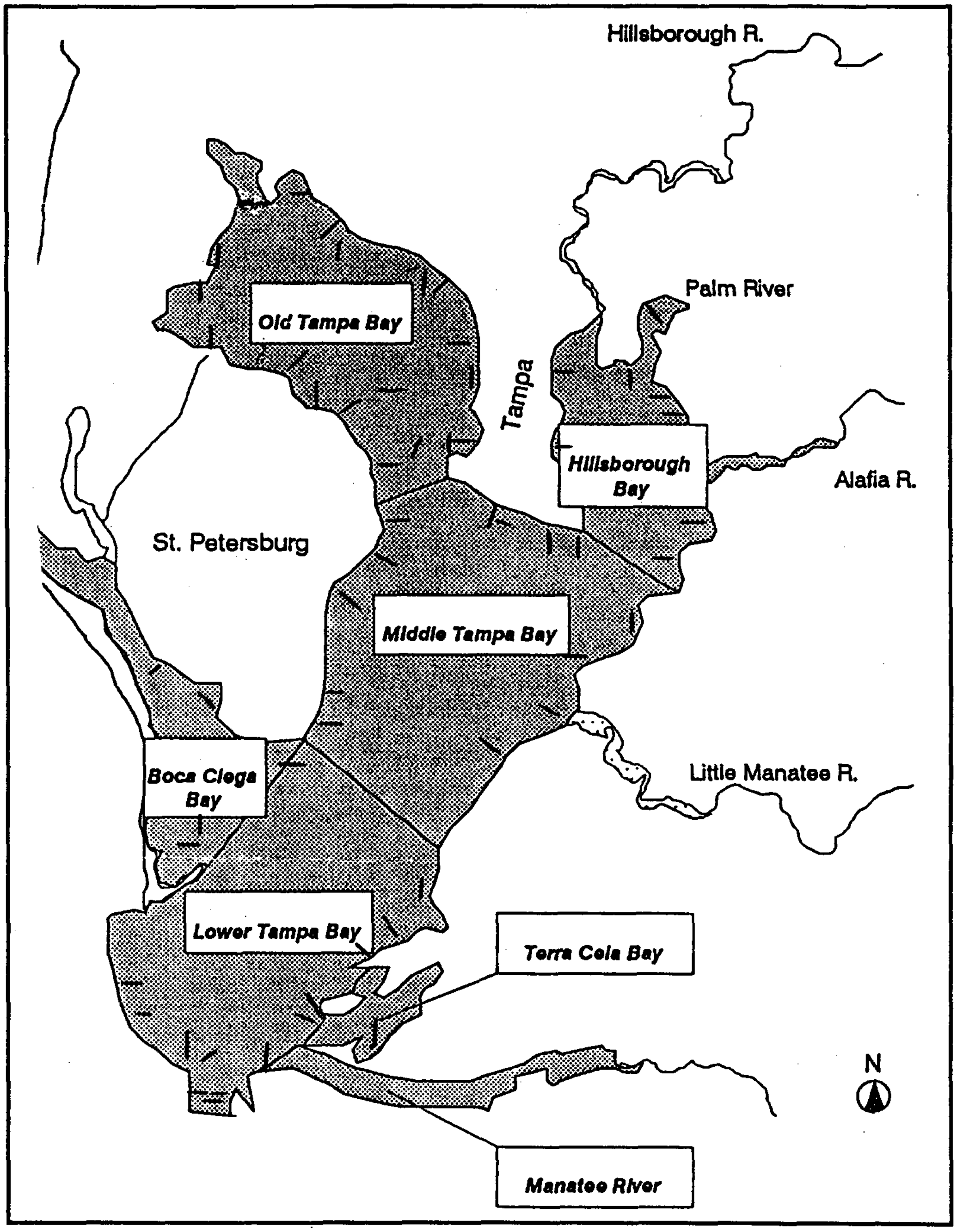
by

Thomas Ries
Southwest Florida Water Management District
Tampa Service Office
7601 U.S. Highway 301
Tampa, FL 33637

In Tampa Bay we gained similar knowledge to that gained by Bob Virnstein and his colleagues with seagrass mapping. We are finding important site specific information when we enter the field to take a closer look at the transect. The GIS map supplies the overall picture of Tampa Bay, while the transects provide site specific information on species presence and overall physical constraints. We use the same parameters as mentioned earlier, in addition to water depth and bottom composition.

Figure 1 shows where the seventy 1,000 meter transects are located throughout the Tampa Bay area. All are located along the shoreline within 2 meters of water, with the majority being perpendicular to the shore. All the information in our seagrass mapping program is available on the GIS system and can be ordered by calling the District. In addition, we plan to use the bathymetric information from the Department of Environmental Protection as an overlayer to the GIS system. We plan to conduct a trend analysis between one meter and two meter contours, as well as trend analysis by quad, examining what kind of increases and decreases are found and where these differences are located.

Figure 1. Marked site specific transects in Tampa Bay.



PHYSIOLOGICAL MEASURES OF SEAGRASS HEALTH

by

David A. Tomasko, Ph.D.
Sarasota Bay National Estuary Program
1550 Ken Thompson Highway
Sarasota, FL 34236

OVERVIEW

The health of seagrasses within a given area, at a given time, can be assessed to some degree by determining the quantities and/or activities of various physiological indicators. Physiological indicators include proximate constituents, pigment levels, indicator enzymes, and stress proteins. In combination with appropriately designed field and/or laboratory studies, information on physiological markers can be very informative and insightful.

PROXIMATE CONSTITUENTS

The relative quantities of chemical constituents of seagrasses can vary with season, water depth, and geographic location (Dawes *et al.*, 1979; Dawes and Lawrence, 1980; Tomasko and Dawes, 1990). In addition, cropping or blade loss can invoke changes in constituent levels (Dawes *et al.*, 1979; Dawes and Lawrence, 1979; Tomasko and Dawes, 1989a, b).

Protein content can vary as a function of sediment nutrient supply, in a manner similar to that of fluctuations in tissue N and tissue P contents mirroring availability of sediment nutrients (Short, 1987; Fourqurean *et al.*, 1992a, b).

Levels of soluble carbohydrates in rhizomes and short shoots track seasonal changes in carbon allocation strategies (Dawes *et al.*, 1979; Tomasko and Dawes, 1990), with levels increasing in times of energy storage, and decreasing when reserves are drawn upon for basic metabolism or rapid growth. Additionally, soluble carbohydrate stores are drawn upon when stresses such as light reduction and/or leaf removal are imposed (Dawes *et al.*, 1979; Tomasko and Dawes, 1989a, b; Hall, pers. commun.).

In contrast, levels of lipid, ash, and insoluble carbohydrate vary little as a function of location, season, or other factors. As such, they would not appear to be profitable subjects for investigation.

PIGMENTS

The relationship between decreased light availability and correlative changes in pigment levels and pigment organization is illustrated in Table 1. Of the 12 scenarios examined for reducing available light to seagrasses, 10 found that P_{max} (the photosynthetic rate at saturating irradiance) declined with decreasing light levels. This relationship persisted whether decreased light was due to increased water depth, seasonal shifts in water clarity, or actual shading of intact plants.

Alpha, the initial slope of the photosynthesis-irradiance (PI) curve, seemed to vary independently of light availability, as did the ratio between chlorophyll *a* and chlorophyll *b*. However, total chlorophyll levels increased with decreased light availability in 8 of the 10 scenarios that examined this relationship.

Consequently, it appears that pigment levels and P_{max} values might be useful indicators of spatial and/or seasonal differences in light availability. Whether the reason for decreased irradiance is increased water depth, increased distance from a flushing inlet or some other factor, reduced irradiance should manifest itself in lower P_{max} values and higher blade chlorophyll levels.

INDICATOR ENZYMES

The major indicator enzymes to receive much attention from seagrass researchers are Alcohol Dehydrogenase (ADH), Nitrate Reductase (NR), and various carbon metabolizing enzymes. As light levels decrease, photosynthesis would decrease. Persistent low photosynthetic rates might induce localized rhizosphere anoxia, particularly in organic-rich sediments. As ADH allows for continued metabolism in the absence of available oxygen, ADH has been shown to be a good indicator of root anoxia (Smith *et al.*, 1984). Consequently, ADH activity might be a good stress indicator in areas where reduced light is thought to be co-occurring with degrading

Table 1. Responses of the photosynthetic processes of various species of submerged aquatic macrophytes to decreased irradiance. "NA" = no available information. "0" = no change with decreased light. "+" = increase with decreased light. "-" = decrease with decreased light.

Study	Reason for Decreased PAR	Pmax	Alpha	Total Chl	Chl a:b
1	Depth	NA	NA	+	-
2	Depth	-	NA	+	0
2	Shade	0	NA	+	0
3	Season	-	0	+	+
4	Season	-	-	NA	NA
4	Depth	-	-	NA	NA
5	Season	-	0	+	+
5	Depth	-	0	0	0
6	Depth	-	NA	+	-
7	Depth	-	NA	+	-
8	Depth	-	0	0	NA
9	Shade	-	+	+	-

1) Wiginton & McMillan, 1979
2) Dennison & Alberte, 1985
3) Drew, 1978
4) Libes, 1986
5) Pirc, 1986
6) Dennison & Alberte, 1986
7) Dennison & Alberte, 1982
8) Dawes & Tomasko, 1988
9) Goldsborough & Kemp, 1988

water quality. The activities of enzymes such as sucrose phosphate synthase and sucrose synthase are also good indicators of the rates of source-to-sink carbon transport and carbon transformations (Zimmerman and Alberte, 1990).

In an intriguing series of experiments, both Maier and Pregnall (1990) and Burkholder *et al.* (1992) found evidence that Nitrate Reductase (NR) was an inducible enzyme in seagrass leaves, with increased activities in areas of elevated nitrate loading. As nutrient enrichment of nearshore waters is a major cause of seagrass declines worldwide, NR might be a useful tool for locating areas where significant nitrate enrichment of nearshore waters is occurring. Burkholder *et al.* (1992) argue that nitrate enrichment of nearshore waters in North Carolina is of sufficient magnitude to cause direct mortality of seagrasses through a process that accelerates carbon withdrawal from storage tissues.

STRESS PROTEINS

In agricultural crops such as rice and wheat, stress proteins have received much attention as markers of various physiological insults. Stress proteins are evolutionarily very conservative, and they function to minimize the effects of various agents on degradation of cellular proteins. Factors such as recurrent anoxia, pesticides and heavy metals can induce the formation of stress proteins. Despite the great potential for using stress proteins as molecular markers of degraded habitat quality, no work has been published on the subject of stress proteins in seagrasses.

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SAVI SECTION 4:

MODELING PAR AS A FUNCTION OF WATER QUALITY

USE OF PAR MODELS FOR SCIENCE AND MANAGEMENT

by

Robert W. Virnstein, Ph.D.
St. Johns River Water Management District
P.O. Box 1429
Palatka, FL 32178

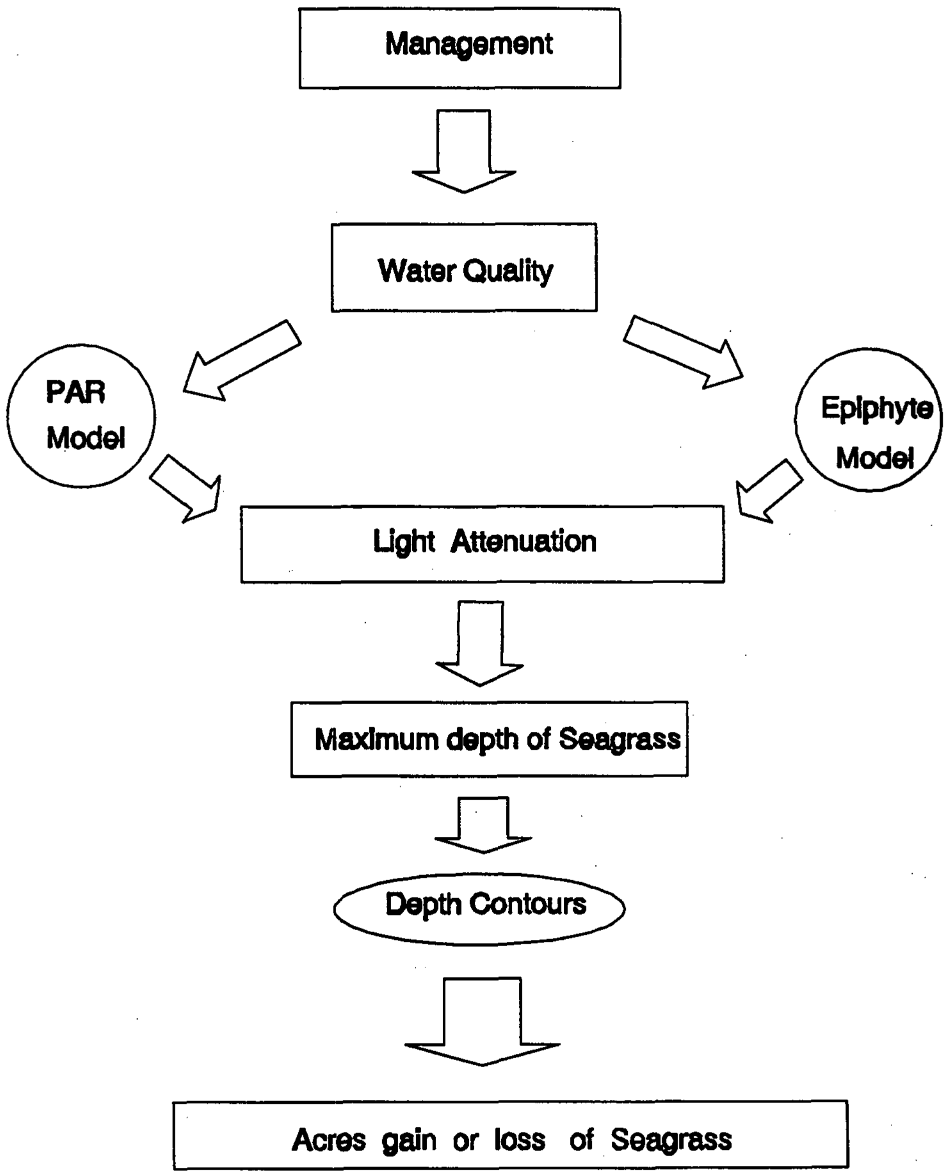
"So What?" This is the question we need to keep asking ourselves. How we will use any piece of information to improve or protect seagrass?

The simple model in Figure 1 illustrates how the components are fit together. Simply in terms of steps, we need to move in steps from management actions to acres of gain or loss of seagrass and seagrass functions. These steps include measuring various water quality parameters such as suspended solids, color, and chlorophyll and using the light model to relate these parameters to light attenuation. In addition to this light attenuation by the water column, we also need to consider the effects of epiphytes, which decrease the amount of light actually reaching the surface of seagrass blades. Calculations from the water column and epiphyté models predict maximum depth of seagrass in a given area. If we know depth contours, we can relate that information to a change in potential acres of seagrass (Figure 1).

This model can be used in many ways for management of the Lagoon's resources. For example, we would like to be able to go to a city interested in building a sewer treatment plant, and answer officials' questions about potential impacts on resources. Knowing the water quality, depth contours, and hydrodynamics of the area, we could use the model to predict changes in water quality parameters and thus predict the potential increase in seagrass acreage.

To develop these models will require an understanding of critical time periods and appropriate sampling schedules; these are difficult to determine. Critical light periods may be more relevant than average light levels. For example, during the winter, there are low light levels and low temperatures, less plant biomass, and less oxygen demand. Conversely, in the summer, there is a higher biomass, particularly a high leaf biomass, which has a larger respiration demand. Temperatures are very

Figure 1.


Management
Water Quality
PAR Model
Epiphyte Model
Light Attenuation
Maximum depth of Seagrass
Depth Contours
Acres gain or loss of Seagrass

high and there is a lot of organic matter. Low light levels for a short period may be critical. Measuring average light levels might be less important than intensively measuring light levels during the critical period. For maximum information content, we might time the sampling periods to natural events, such as the maximum plant biomass or maximum temperature, when light levels may be critical. For example, during the winter when seagrasses lose many of their leaves and the low temperatures mean low oxygen demand, it may not matter whether there is a lot of light, and it would be fruitless to spend much effort measuring light levels then.

However, some fruitful areas to examine might include the following:

* How long are certain light levels needed?
* Critical periods versus chronic levels
* Timing of measurements relative to natural plant cycles
* Temperature cycles relative to attenuation cycles.

Besides water column parameters, epiphytes also reduce the light reaching seagrass blades. The abundance of epiphytes is determined by (1) nutrients, (2) grazers of the epiphytes, such as snails and amphipods, and (3) the age and growth rate of the seagrass blades. The model should incorporate all factors so that we will be able to say that, given A conditions and B factors, then C will occur. The model should provide useful answers to management and must be based on good science.

HABITAT REQUIREMENTS OF SAV IN CHESAPEAKE BAY BASED ON WATER QUALITY

by

Robert J. Orth, Ph.D.
School of Marine Science
Virginia Institute of Marine Science, College of William and Mary
Gloucester Point, VA 23062

Worldwide, estuaries are experiencing water quality problems as a result of the pressures from increasing numbers of people moving to coastal areas. Chesapeake Bay, one of the world's largest estuaries, has experienced deterioration of water quality from nutrient enrichment resulting in anoxic or hypoxic conditions and declines in living resources. Determination of relationships between water quality and various living resources provides a mechanism of relating anthropogenic inputs to the "health" of Chesapeake Bay. In particular, the establishment of habitat requirements and restoration targets for critical species living in Chesapeake Bay is a way in which scientists, resource managers, politicians and the public can work toward the goal of restoring the Chesapeake Bay.

One of the major factors contributing to the high productivity of Chesapeake Bay has been the historical abundance of SAV. SAV in Chesapeake Bay include some 20 freshwater and marine species of rooted flowering plants. SAV provide food for waterfowl and are critical habitat for shellfish and finfish. SAV also affect nutrient cycling, sediment stability and water turbidity. However, a bay-wide decline of all SAV species in Chesapeake Bay began in the late 1960s and early 1970s. This SAV decline was related to increasing amounts of nutrients and sediments in the Bay resulting from development of the Bay's shoreline and surrounding watershed.

Information presented here has been previously published. Please cite original source:
Dennison, W.C., R.J. Orth, K.A. Moore, J.C. Stevenson, S. Kollar, P.W. Bergstrom, and R.A. Batiuk. 1993. Assessing Water Quality with Submerged Aquatic Vegetation. Bioscience, 43:86-94.

Figure 1. Conceptual model of SAV and habitat interaction

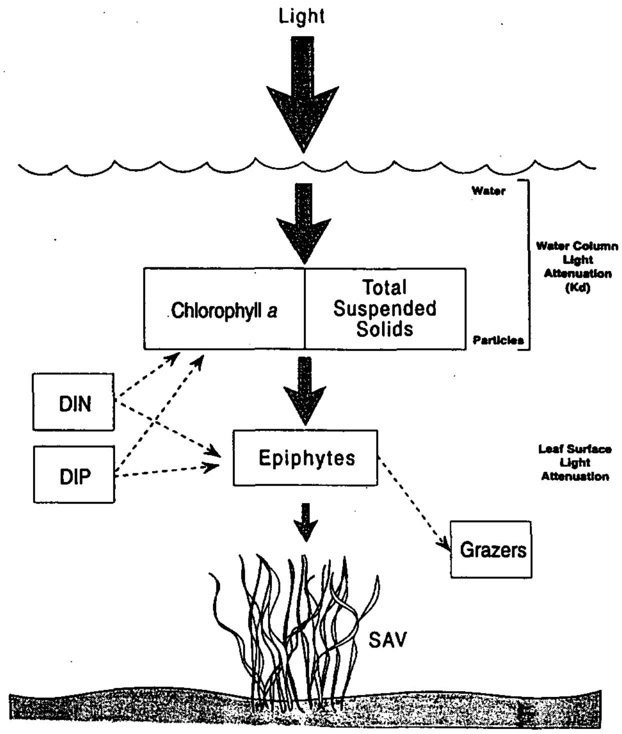
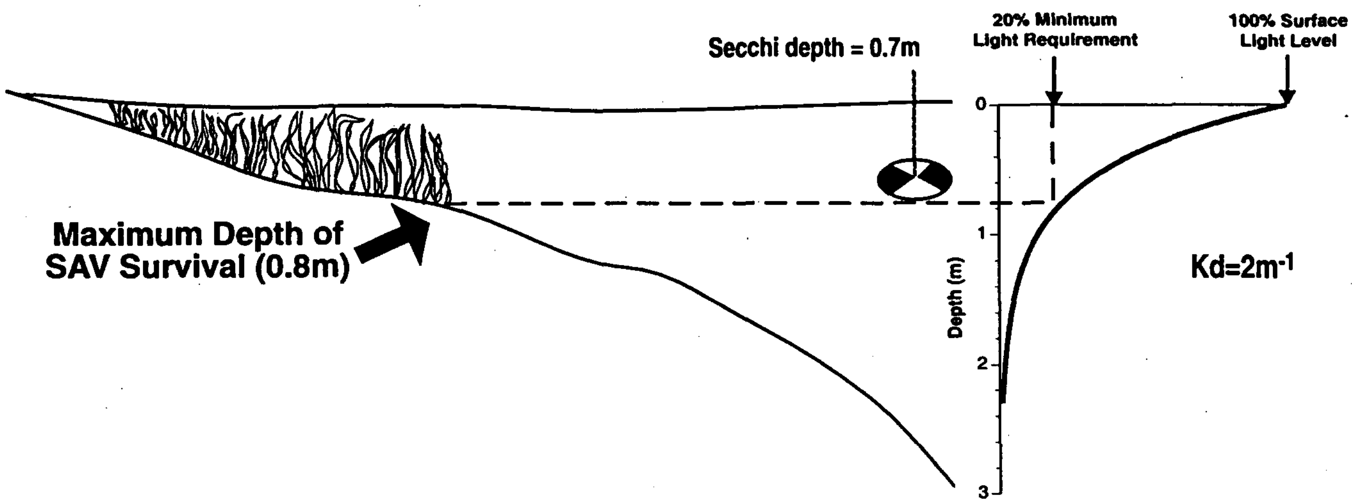


Figure 2. Determination of Maximum depth of SAV survival.



One Meter Restoration Habitat Requirement for Light Attenuation

The Chesapeake Executive Council's adoption of the Chesapeake Bay Submerged Aquatic Vegetation Policy and an Implementation Plan for the SAV Policy (Appendix III) highlighted not only the need to develop SAV habitat requirements but also the need for bay-wide restoration goals for SAV distribution, density and species diversity. In response to the commitments described in the SAV Policy Implementation Plan, a working group of scientists and managers produced the "Chesapeake Bay Submerged Aquatic Vegetation Habitat Requirements and Restoration Targets: A Technical Synthesis."

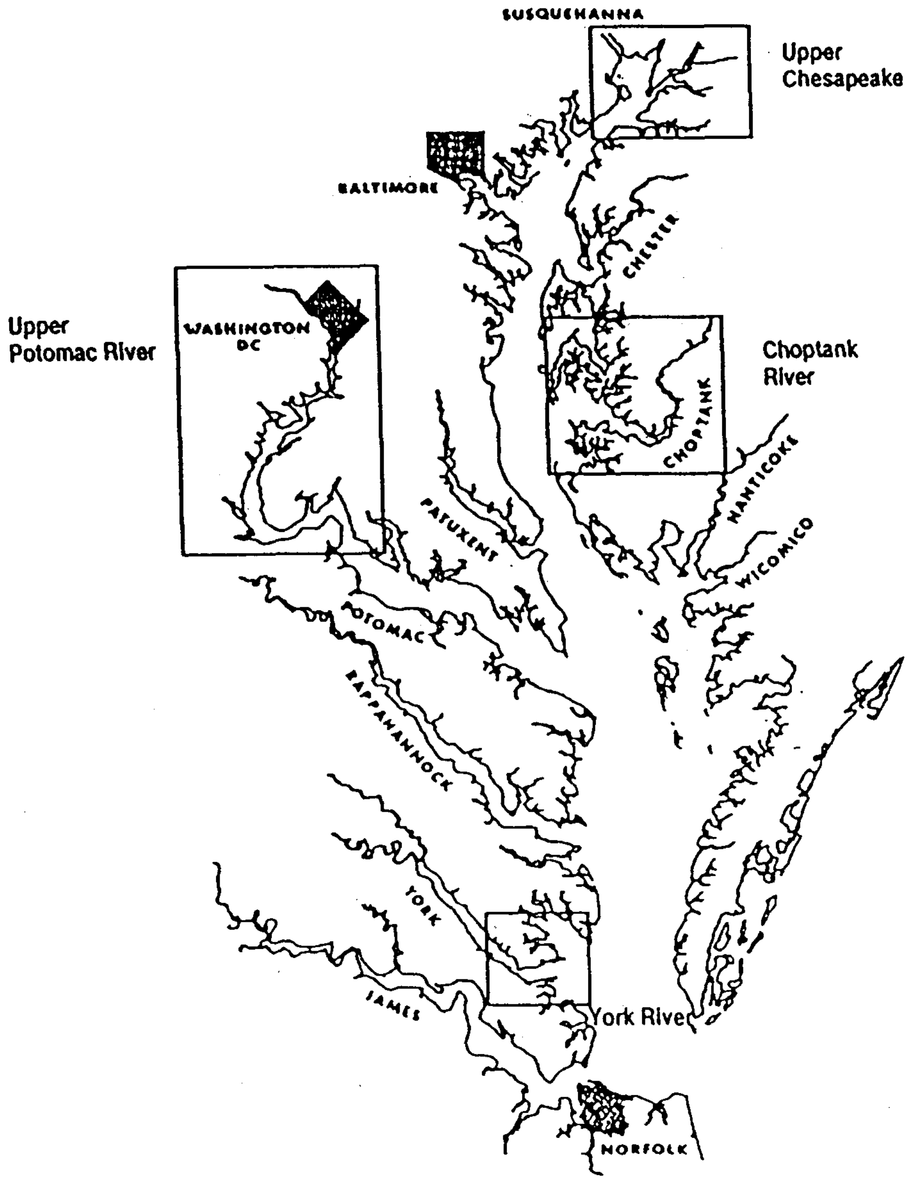
The primary objective of the SAV Technical Synthesis is to establish the quantitative levels of relevant water quality parameters necessary to support continued survival, propagation, and restoration of SAV. Secondary objectives are to: establish regional SAV distribution, density and species diversity targets for Chesapeake Bay and its tributaries; document the bay-wide applicability of habitat requirements developed through the case studies in the synthesis; and assess the applicability of mid-channel monitoring data for evaluating the water quality in adjacent shallow water habitats.

A conceptual model of the interactions and interdependence of the SAV habitat requirements (Figure 1) illustrates the water quality parameters that influence SAV distribution and abundance. A wealth of scientific studies from around the world have established the importance of light availability as the major environmental factor controlling SAV distribution, growth and survival. The primary environmental factors contributing to light attenuation are used to formulate SAV habitat requirements: light attenuation coefficients, chlorophyll a, total suspended solids, dissolved inorganic nitrogen and dissolved inorganic phosphorus.

The minimum light requirements of a particular SAV species determines the maximum water depth for survival. This can be depicted graphically as the intersection of the light intensity versus depth curve with the minimum light requirement value (Figure 2). Light is attenuated exponentially with water depth (Figure 2, right side). The minimum light requirement of a particular SAV species, as a percent of incident light, intersects the light curve to give a predicted maximum depth of SAV survival for that species (Figure 2, left side).

Four study areas were used to develop specific relationships between SAV survival and water quality (Figure 3). These study areas represent regions of intensive SAV studies over the past decade in which water quality data, and SAV growth, distribution, density and transplant data were available. Empirical relationships developed between water quality characteristics and SAV distributions provided the

Figure 3. Locations of the four regional SAV study areas -- upper Chesapeake Bay, upper Potomac River, Choptank River, and York River.



means of defining habitat requirements for SAV survival. It is the application of these SAV/water quality relationships from the case studies in different regions of Chesapeake Bay, by different investigators over the span of several years that forms the basis of the SAV habitat requirements.SAV habitat requirements are defined as the minimal water quality levels necessary for SAV survival. Water quality parameters used in the delineation of habitat requirements were chosen because of their relevance to SAV survival. SAV habitat requirements were formulated by a) determining SAV distributions by transplant survival and bay-wide distributional surveys, b) measuring water quality characteristics along large scale transects that spanned vegetated and non-vegetated regions, and c) combining distributional data and water quality levels to establish minimum water quality that supports SAV survival. This type of analysis (referred to as correspondence analysis) was strengthened by factors common to each of the case studies. Field data was collected over several years (almost a decade in the Potomac River) in varying meteorologic and hydrologic conditions by different investigators.

SAV distribution in four case studies across all salinity regimes were responsive to the five water quality parameters used to develop the SAV habitat requirements. The degree of interdependence of these water quality parameters is illustrated by a three-dimensional plot of total suspended solid, chlorophyll *a* and light attenuation coefficient for the Choptank River (Figure 4). In addition, interannual changes in water quality led to changes in SAV distribution and abundance in each region that were consistent with habitat requirements.

The diversity of SAV communities throughout Chesapeake Bay, with its wide salinity range, has led to the establishment of separate habitat requirements, based on salinity regime. Water quality conditions sufficient to support survival, growth and reproduction of SAV to water depths of one meter are used as SAV habitat requirements (Table 1).

For SAV to survive to one meter, light attenuation coefficients of less than 2 m^{-1} for tidal, fresh and oligohaline regions and less than 1.5 m^{-1} for mesohaline and polyhaline regions were needed.

Total suspended solids (less than 15 mg/l) and chlorophyll *a* (less than 15 ug/l) values were consistent for all regions. However, habitat requirements for dissolved inorganic nitrogen and dissolved inorganic phosphorus varied substantially between salinity regimes.

Table 1.

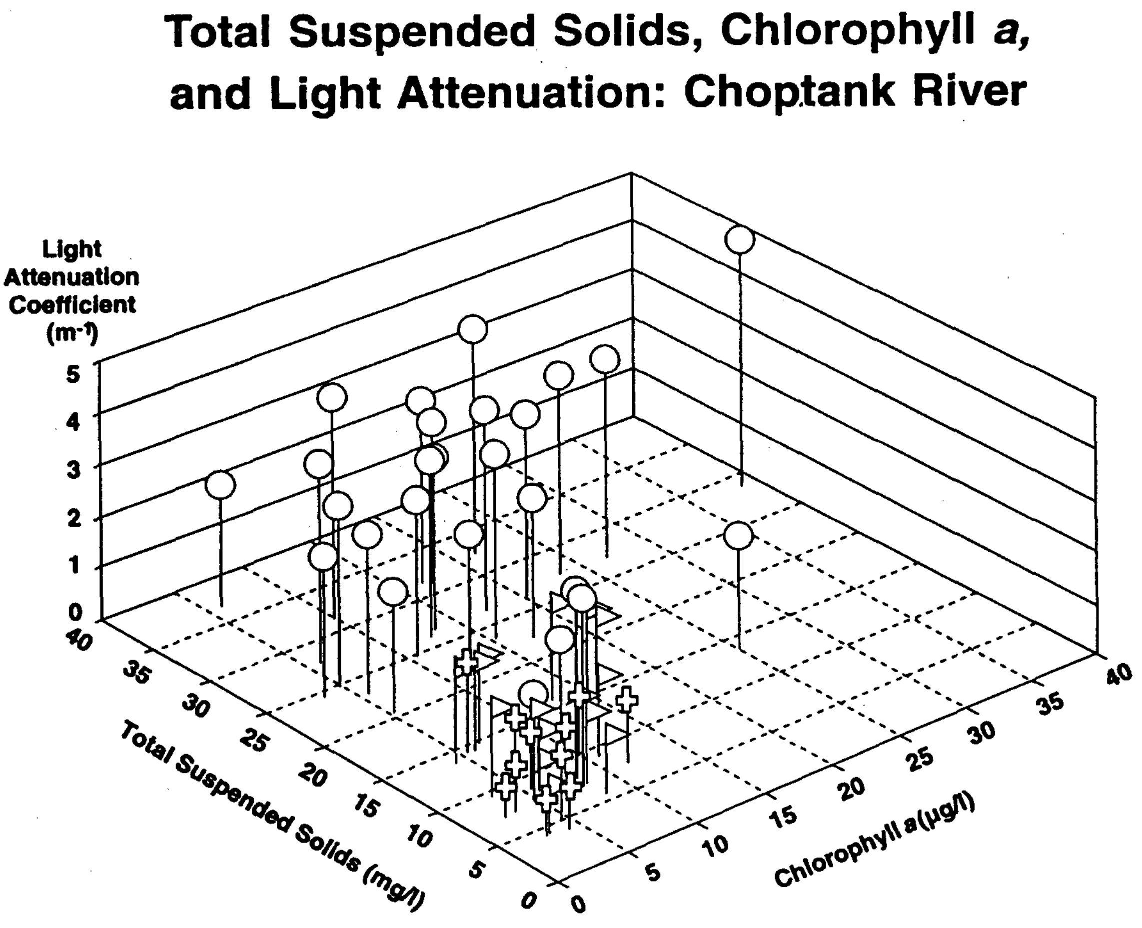
Chesapeake Bay SAV Habitat Requirements								
SAV Habitat Requirements For One Meter Restoration[1]							SAV Habitat Requirements For Two Meter Restoration	
Salinity Regime[2]	Light[3] Attenuation Coefficient (m^{-1})	Total Suspended Solids (mg.l)	Chlorophyll *a* (µg/l)	Dissolved Inorganic Nitrogen (mg/l)	Dissolved Inorganic Phosphorus (mg/l)	Critical Life Period	Light Attenuation Coefficient (m^{-1})	Critical Life Period
Tidal Fresh	<2	<15	<15	—	<0.02	April-October	<0.8	April-October
Oligohaline	<2	<15	<15	—	<0.02	April-October	<0.8	April-October
Mesohaline	<1.5	<15	<15	<0.15	<0.01	April-October	<0.8	April-October
Polyhaline	<1.5	<15	<15	<0.15	<0.02	March-Novemb.	<0.8	March-Novemb.

[1] The SAV habitat requirements are applied as median values over April-October critical life period for tidal fresh, oligohaline, and mesohaline salinity regimes. For polyhaline salinity regimes, the SAV habitat requirements are applied as median values from combined March-May and September-November data.

[2] Tidal fresh ≤ 0.5 ppt; oligohaline = 0.5 - 5.0 ppt; mesohaline ≥ 5.0 - 18.0 ppt; and polyhaline ≥ 18.0 ppt.

[3] For determination of Secchi depth habitat requirements, apply the conversion factor: Secchi depth = 1.45 / light attenuation coefficient.

Figure 4. Three dimensional comparisons of May-October median light attenuation coefficient, total suspended solids, and chlorophyll *a* concentration of the Choptank River Stations. Cross = persistent SAV; Flag = Fluctuating SAV; Circle = SAV absent.



In tidal, freshwater, and oligohaline regions, SAV survive episodic and chronic high concentrations of dissolved inorganic nitrogen, consequently habitat requirements for dissolved inorganic nitrogen were not determined for these regions. In contrast, maximum dissolved inorganic nitrogen concentrations of 0.15 mg/l were established for mesohaline and polyhaline regions. The SAV habitat requirement for dissolved inorganic phosphorus was less than 0.02 mg/l for all regions except for mesohaline regions (less than 0.01 mg/l). Differences in nutrient habitat requirements in different regions of Chesapeake Bay are consistent with observations from a variety of estuaries that shifts in the relative importance of phosphorus versus nitrogen as limiting factors occur over an estuary's salinity gradient.

Application of Chesapeake Bay SAV habitat requirements developed in the four study areas to the rest of the Chesapeake Bay was conducted to test the bay-wide correspondence of SAV distributions with the five water quality parameters measured at mid-channel monitoring stations. SAV growing season median water quality values were calculated for 105 monitoring stations in the Chesapeake Bay and its tidal tributaries for 1987 and 1989, with 1989 results summarized here (Table 2).

Table 2.

Five SAV Habitat Requirements to Growing Season Medians of Data From Chesapeake Bay

Salinity Regime	Habitat Requirements				
	KD	TSS	CHL *a*	DIN	DIP
Tidal Fresh	100% (1)	100% (1)	100% (1)	-	100% (1)
Oligohaline	0% (1)	0% (1)	100% (1)	-	100% (1)
Mesohaline	95% (19)	79% (19)	100% (19)	68% (19)	95% (19)
Polyhaline	100% (11)	55% (11)	100% (11)	100% (11)	100% (11)
ALL	**94% (32)**	**69% (32)**	**100% (32)**	**80% (30)**	**97% (32)**

The number of stations in each salinity regime, in areas with or without SAV, was tabulated according to whether each of the five habitat requirements were met or not met. If the habitat requirements were perfect predictors of SAV growth, 100 percent of the stations with SAV would have met all the habitat requirements.

Table 2 shows that five habitat requirements have slightly differing abilities to predict SAV presence: Light attenuation coefficient (94 percent), total suspended solids (69 percent), chlorophyll a (100 percent, dissolved inorganic nitrogen (89 percent), and dissolved inorganic phosphorus (97 percent). The overall average for all parameters is fairly high and indicates the utility of this approach.

The 1990 SAV distribution indicate that current SAV abundance (24,394 hectares) is 51.5 percent of the Tier I target and only 9.7 percent of the Tier II target (Table 3). These estimates provide a baseline on which the success of nutrient and sediment reduction strategies for the Chesapeake Bay can be assessed.

Table 3.

Chesapeake Bay SAV Distribution Targets and Their Relationship to 1990 SAV Aerial Survey Distribution Data

Restoration Target	Description	Area (hectares)	1990 SAV Distribution and Percent of Restoration Target
Tier I- composite beds	Restoration of SAV to areas currently or previously inhabited by SAV, as mapped through regional and bay-wide aerial surveys	47,382	24,394 (51.5%)
Tier II-one meter	Restoration of SAV to all shallow water areas delineated as existing or potential SAV habitat down to the one meter depth excluding areas identified as unlikely to support SAV based on historical observations, recent survey information, and exposure regimes.	-	In Progress
Tier III-two meter	Restoration of SAV to all shallow water areas delineated as existing or potential SAV habitat down to the two meter contour excluding areas identified under the Tier II target as unlikely to support SAV as well as several additional areas between 1 and 2 meters.	250,824	24,394 (9.7%)

The nearshore/mid-channel water quality comparison was organized around the same four study ares. Results of this comparison indicate mid-channel water quality data can be used to characterize nearshore areas over seasonal time frames, but do not imply a predictive relationship between nearshore and mid-channel observations. Seasonal aggregations of mid-channel water quality data can provide reliable estimates of nearshore water quality conditions for the parameters examined in this study.

The technical synthesis represents a first comprehensive effort to link habitat requirements for a living resource with water quality restoration targets for an estuarine system. This habitat requirement approach, while deviating from the traditional dose-response measures and direct toxicity studies, provides testable hypotheses that can be explored in future studies in other estuaries. Additional experimental evidence using field and laboratory approaches to test the empirical relationships developed in this synthesis are necessary for development of water quality criteria, with a goal of improved predictive capacity of habitat requirements.

SAV habitat requirements represent the absolute minimum water quality characteristics necessary to sustain plants in shallow water. As such, exceeding any of the five water quality characteristics will seriously compromise the chances of SAV survival. Improvements in water clarity to achieve greater depth penetration of SAV would not only increase depth penetration, but also increase SAV density and biomass. In addition, improvements of water quality beyond the habitat requirements could lead the maintenance or reestablishment of a diverse population of native SAV species.

We need to maintain continuous interactions and feedback between the researchers who continue to investigate SAV/water quality interactions and the managers who are responsible for ultimate protection, restoration, and enhancement of living resources. Continued research and monitoring of water quality and SAV, coupled with management towards specific restoration targets, is paramount if these resources are to be part of our future.

DEVELOPMENT OF OPTICAL MODELS FOR PROTECTION OF SEAGRASS HABITATS [1]

by

Charles L. Gallegos, Ph.D.
Smithsonian Environmental Research Center
P. O. Box 28
Edgewater, MD 21037

Dr. Gallegos received his B.A. in zoology from Duke University in 1973, and continued on for a Ph.D. in environmental sciences at the University of Virginia in 1979. During 1979 and 1980, he was a postdoctoral fellow at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia. There he studied phytoplankton photosynthesis-irradiance relationships and the effects of vertical transport on phytoplankton photosynthesis. He served as a hydrologist from 1981-86 for the U.S. Department of Agriculture, Agricultural Research Service in Oklahoma. There he researched agricultural management practices in water quality, water quality modeling of farm impoundments, and optical properties of turbid farm ponds. Since 1986, he has worked at the Smithsonian Environmental Research Center in Edgewater, MD, as a microbial ecologist. His main interest is primary productivity and population dynamics of phytoplankton in eutrophic estuaries, optical properties of turbid estuarine, and optical water quality models for protecting seagrass habitats.

INTRODUCTION

It is well known that seagrasses have high light requirements (*reviewed by* Dennison *et al.*, 1993). Light requirements for seagrasses are usually expressed as annual or growing season averages of the percentage of incident irradiance reaching the depth limit of observed grass beds. Requirements estimated in this way differ among species and sites, but generally range from about 10 to 30 percent (Duarte, 1991). Many details of the light requirements remain to be determined. Are seagrass depth limits determined by chronic, average levels of turbidity, or by acute, transient reductions in light penetration? Is maintenance of adequate light penetration during certain portions of the growing season especially important? Whatever is determined about the biological light requirements of various seagrass species, development of

[1] When citing results pertaining to Chincoteague Bay, Rhode River, or Model Development, please refer to Gallegos (in press, see LITERATURE CITED).

effective management plans will depend on translation of light requirements of the plants into concentration goals for various water quality constituents that affect light penetration. This paper outlines an approach being taken to relate light penetration to water quality by modeling optical properties of water, and summarizes results of application of the approach to Chincoteague Bay and the Rhode River, MD, contained in a pending paper (Gallegos, in press).

Model Development

The empirical descriptor of the light available at a depth in terms of that available at the surface is the diffuse attenuation coefficient of downward propagating irradiance, k_d, defined as

$$k_d = -\frac{1}{z}\ln\left(\frac{E_z}{E_{0^-}}\right) \qquad (1)$$

where E_z is the irradiance available at depth z, E_0- is the irradiance just below the surface (0-) (Morel and Smith, 1978). The definition is useful because the decrease in irradiance with depth is approximately exponential. Once the fraction of surface light required by the seagrasses is known, say for example 20%, then the depth to which that fraction of light penetrates, Z_{20}, may be calculated readily as $-\ln(0.20)/k_d$.

The diffuse attenuation coefficient is referred to as an apparent optical property, because it depends on properties of the ambient light field as well as on the contents of the water (Kirk, 1983). The diffuse attenuation coefficient does not exist at night when there is no sun, and it depends on, among other things, the solar elevation angle and the extent of cloud cover. Properties that only depend on the contents of the water are called inherent optical properties (Kirk, 1983), and it is these that determine the magnitude of k_d for a particular solar elevation angle. A useful expression for the dependence of k_d on the inherent optical properties a_t, the total absorption coefficient, and b, the scattering coefficient, was given by Kirk (1984)

$$k_d = \frac{1}{\mu_0}[a_t^2 + G(\mu_0)a_t b]^{\frac{1}{2}} \qquad (2)$$

where μ_0=cosine of the zenith angle of the direct solar beam (a function of latitude, date, and time of day) refracted at the air-water interface, and $G(\mu_0)$ is a function of the form

$$G(\mu_0) = g_1\mu_0 - g_2 \tag{3}$$

that modifies the interaction between scattering and absorption; g_1 and g_2 are empirically determined coefficients that depend on the optical depth of interest (Kirk, 1991).

For modeling light penetration in relation to water quality, there are advantages to working with inherent optical properties. First, inherent optical properties are additive; that is, total absorption or scattering may be expressed as the sum of absorption or scattering due to individual components in the water. This is not true for the diffuse attenuation coefficient (Kirk, 1983). Thus, we can express the total absorption coefficient as

$$a_t = a_y + a_p + a_w \tag{4}$$

where a_y=absorption by dissolved yellow matter (i.e. color), a_p=absorption by particulate matter, and a_w=absorption by water itself. Absorption by particulate matter may be further decomposed into contributions due to mineral and organic detritus, a_d, and that due to phytoplankton, a_{ph}. That is,

$$a_p = a_d + a_{ph} \tag{5}$$

Another important characteristic of inherent optical properties is that they are strictly linear. Thus we may express the absorption by any particular component, X, as the product of the concentration of that component and a coefficient referred to as an optical cross section. For absorption,

$$a_X = \sigma_X[X] \tag{6}$$

where σ is the optical absorption cross section, and X stands for the constituent of interest.

The modeling problem is to determine these optical cross sections for each important water quality constituent. In general each of the cross sections is a function of wavelength. For certain components the wavelength dependence has a compact mathematical representation. For example, absorption by color may be expressed

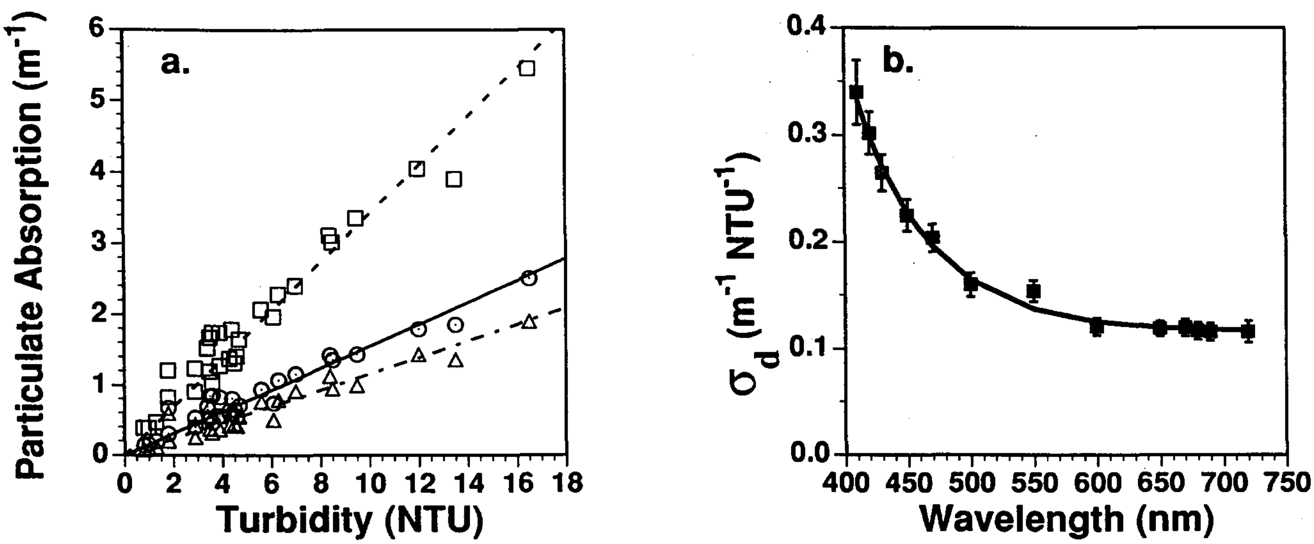
$$a_y(\lambda) = g_{440}\exp[-s_y(\lambda - 440)] \qquad (7)$$

where g_{440} is the absorption by dissolved matter at 440 nm, s_y is a spectral slope for dissolved matter, and λ=wavelength. Similarly, at Chincoteague Bay, MD, absorption by suspended detrital particulates was found to be proportional to turbidity [Turb], and was expressed (Gallegos, in press; *see below*, Figure 1).

Figure 1. Absorption by non-algal particulate matter in Chincoteague Bay, MD.

a. Absorption coefficient at : -□- 410nm; --○-- 550nm; · - △ - · 720nm as a function of turbidity.

b. Slopes of regressions (σ_d) of particulate absorption against turbidity as a function of wavelength. Error bars are 1 S.E. of regression slopes. Fitted curve is eq. 8b.



$$a_d(\lambda) = \sigma_d(\lambda)[\text{Turb}] \tag{8a}$$

$$\sigma_d(\lambda) = \sigma_{bl} + \sigma_{400}\exp[-s_d(\lambda - 400)] \tag{8b}$$

where σ_d=optical cross section of turbidity, σ_{bl}=baseline absorption at long wavelengths, σ_{400} is a scale factor, and s_d is a spectral slope for particulate detritus. Absorption cross sections for phytoplankton chlorophyll as a function of wavelength are available as tabulated values in the literature. The absorption spectrum of water is also available from the literature.

Estimation of absorption cross sections is accomplished by measurements in the laboratory. g_{440} is measured in a spectrophotometer (10 cm path cell) on filtered water. a_p is measured by collecting particulate matter on a glass fiber filter, which can be scanned in an integrating sphere interfaced to a spectrometer (Gallegos *et al.*, 1990). a_d is measured by soaking the filter in methanol to extract phytoplankton pigments, and scanning the filter again. a_{ph} is then determined by difference (equation 5).

Scattering due to particles far exceeds that due to water itself in estuaries, so that b need not be decomposed into components. Although some studies have found b to be independent of wavelength (Phillips and Kirk, 1984; Witte *et al.*, 1982), more recent studies have indicated that $1/\lambda$ dependence is appropriate (Morel and Gentili, 1991), with $b(550)$=[Turb] (*see e.g.* Vant, 1990; Weidemann and Bannister, 1986). Thus I currently represent scattering by the equation

$$b(\lambda) = \left(\frac{550}{\lambda}\right)[\text{Turb}] \tag{9}$$

MODEL CALIBRATION AND APPLICATION

To implement the model of spectral diffuse attenuation coefficient we need the optical absorption cross sections σ_{bl} and σ_{400}, and spectral slope, s_d, of turbidity, tabulations of the chlorophyll-specific absorption spectrum, $\sigma_{Chl}(\lambda)$, and the spectral slope of dissolved absorption, $s_y(\lambda)$. Roessler *et al.* (1989) recently summarized mean values of s_y (0.014 nm^{-1}), which appears to be fairly constant regionally. The water quality data required to predict the spectrum of diffuse attenuation coefficients according to this model are [Turb], from which b and $a_d(\lambda)$ are predicted using equations (9) and (8b) respectively, [Chl] for estimation of $a_{ph}(\lambda)$ (equation 6), and color as g_{440} for estimation of $a_y(\lambda)$ (equation 7). μ_0 is calculated from location, date, and time of day (Smithsonian Meteorological Tables) and used with equation (2) to predict $k_d(\lambda)$.

Examples of estimation of optical cross-sections are given in Figs. 1 and 2. At a *Zostera marina* bed in Chincoteague Bay, Maryland, absorption by detrital particulates was linearly related to [Turb] (Figure 1a); for clarity only 3 wavebands are shown. Slope of the regression of $a_d(\lambda)$ against [Turb] had a maximum at 400 nm and decreased to a constant baseline in a manner well described by equation 8b (Figure 1b). Estimated parameters in equation 8b for this site were σ_{bl}=0.116 m^{-1} NTU^{-1}, σ_{400}=0.258 m^{-1} NTU^{-1}, s_d=0.0165 nm^{-1}.

Although g_{440} can be measured directly as a water quality parameter, in many monitoring programs only color in Pt units is routinely measured. Recent data from the Indian River near Ft. Pierce, FL, indicate that g_{440} can be reliably estimated from color as conventionally measured (Figure 2). Similar relationships have been determined elsewhere, although the slope of the regression appears to vary regionally (Cuthbert and Del Giorgio, 1992).

Equations 5-9 substituted into (4) and (2) express the dependence of spectral diffuse attenuation coefficient, $k_d(\lambda)$, on water quality variables. To calculate the penetration of PAR from $k_d(\lambda)$, the spectrum of incident sunlight, E_0^-, (Weast, 1977), converted to units of quantum flux density is propagated in 5-nm wavebands to a reference depth, z_r, according to

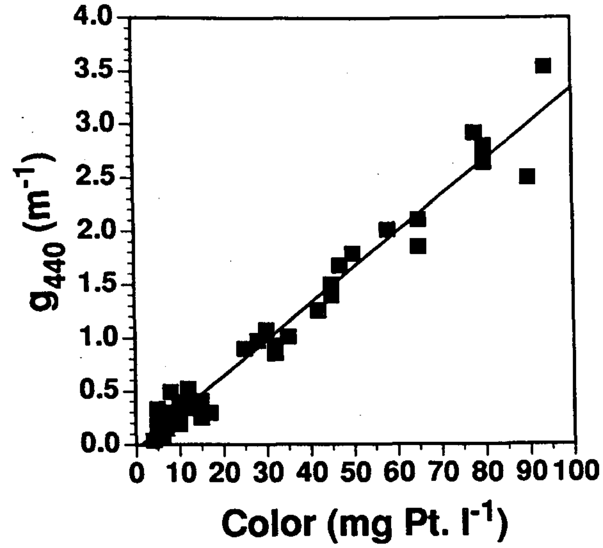
$$E_{z_r}(\lambda) = E_{0^-}(\lambda)\exp[-k_d(\lambda)z_r] \tag{10}$$

At z_r, $\hat{PAR}_z$ is calculated by numerical integration of $E_{zr}(\lambda)$ from λ=400 to 700 nm. The spectrally estimated diffuse attenuation for PAR, $k_d(\hat{PAR})$ is calculated as

$$k_d(\hat{PAR}) = \frac{1}{z_r}\ln\left(\frac{\hat{PAR}_z}{PAR_0}\right) \tag{11}$$

Figure 2. Relationship of absorption by filtered water at 440nm, g_{440}, to color as conventionally measured.

Least squares regression line is $g_{440} = 0.077 \cdot \text{color} - 0.14$, $r^2 = 0.97$, $n = 53$.



where the carat distinguishes spectral estimates from field measurements made with broadband sensors. Z_{20} for PAR is calculated from $k_d(\hat{PAR})$ as described earlier. The model predictions of $k_d(\lambda)$ as well as the numerical integration of equation 10 can be programmed in a spreadsheet for easy, interactive manipulation of water quality concentrations.

One useful application of the optical water quality model is to determine the suitability for SAV survival of water quality conditions not encountered in measured data. This was done for Chincoteague Bay by a Monte Carlo approach in which water quality concentrations were drawn from random distributions and were input to the optical model to calculate spectral and PAR diffuse attenuation coefficients. Prior to investigating conditions not encountered, the model was checked to see if it would reproduce relationships between diffuse attenuation coefficients and water quality within the range of conditions actually encountered at the sites examined (Figures 3, 4). Statistical characteristics of the water quality parameters used in the Monte Carlo simulations were set to match those observed in field data.

Figure 3.

a. Relationship of k_d(PAR) to turbidity for Chincoteague Bay, MD.
(o) measured data; (·) Monte Carlo simulations with optical model.
___ regression on measured data; - - regression on model simulations.

b. As (a) but for chlorophyll concentration.

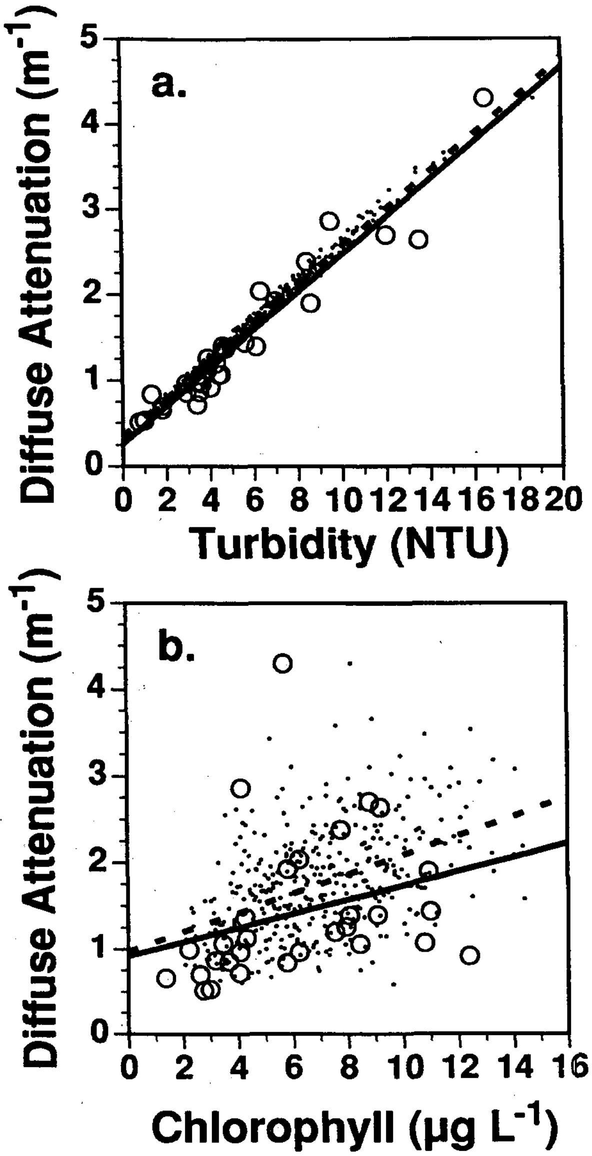
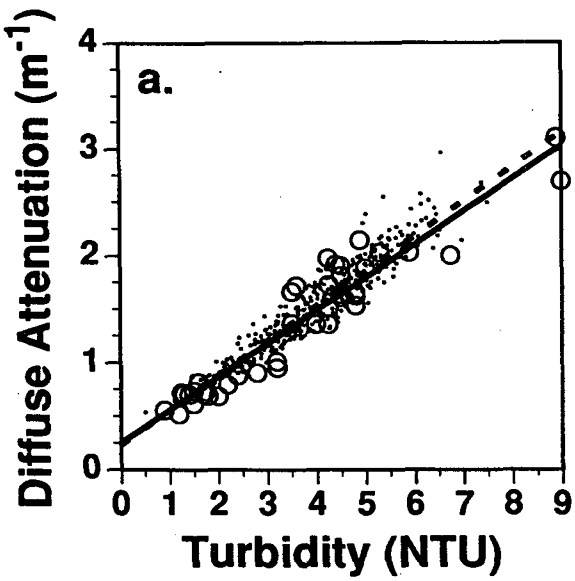
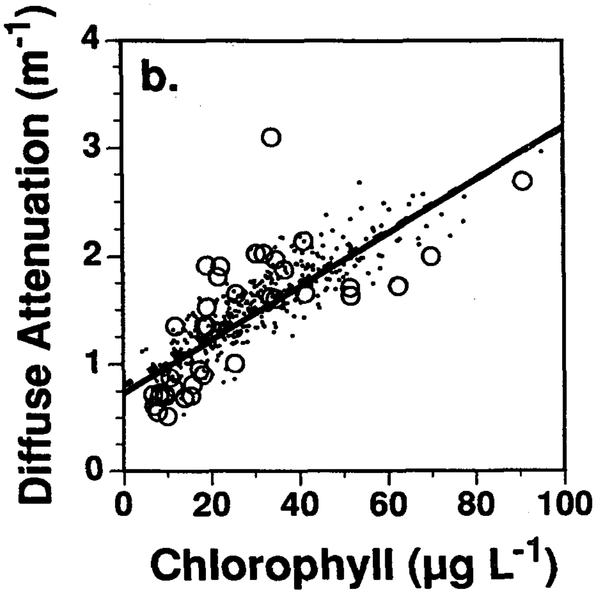


Figure 4.

a. Relationship of diffuse k_d(PAR) to turbidity for Rhode River, MD, USA (o) measured data; (·) Monte Carlo simulations with optical model; ___ Regression on measured data; - - Regression on model predictions.

b. As (a) but for chlorophyll concentrations.





Plots of both simulated and observed k_d(PAR) against [Turb] (Figure 3a) revealed that light penetration in Chincoteague Bay is strongly governed by turbidity. Relationships of k_d(PAR) to [Chl] exhibited much greater scatter (Figure 3b); at Chincoteague Bay a reliable regression between k_d(PAR) and [Chl] cannot be estimated due to the excessive scatter within the narrow range of observed [Chl] (Figure 3b).

To test the sensitivity of the model to higher chlorophyll concentrations, the same optical model was used with water quality distributions chosen to match those observed at the eutrophic Rhode River, MD, a subestuary of Chesapeake Bay. There, diffuse attenuation is also strongly governed by turbidity (Figure 4a), although a greater influence by [Chl] was observed (Figure 4b). Except for the higher correlation between k_d(PAR) and [Turb] in the simulated data for Chincoteague Bay (r^2=0.99 and 0.92 for simulated and observed, respectively), similar regressions and degree of scatter were produced by Monte Carlo application of the model as was observed in the data.

Once calibrated, the optical model is used to determine water quality requirements by varying water quality concentrations, [g_{440}], [Turb], and [Chl] over suitable ranges, and contouring combinations of variables producing predictions of $Z_{20} \geq$ various target depths. In Chincoteague Bay and Rhode River, MD, where dissolved color is low and relatively constant, habitat requirements can be diagramed in terms of turbidity and chlorophyll alone (Figure 5). The numbers on the contours indicate depths to which 20 percent of incident irradiance penetrates. Location of a site on the water quality axes indicates which factors must be reduced to improve growing conditions. For example, when [Chl]=10 $\mu g\ l^{-1}$ and [Turb]=2 NTU, 20 percent of PAR penetrates to about 1.5 m, and no amount of reduction of [Chl] alone will improve penetration to 2 m.

When all three parameters vary over ranges large enough to impact light penetration, presentation of 20 percent penetration depths in 2 dimensions becomes difficult. One alternative is to choose a target depth of interest, say 1 m, and produce contours for that penetration depth with the third variable, color, as a parameter (Figure 6). In this Figure, each contour represents combinations of chlorophyll concentration and turbidity that permit penetration of 20 percent of incident irradiance to 1 m, with color held constant at the value indicated on the contour. For example, when [Chl]=10 $\mu g\ l^{-1}$ and [Turb]=3.2 NTU, color must be <40 mg Pt. l^{-1} to permit penetration of 20 percent surface irradiance to 1 m. Similar diagrams could be generated for other target depths.

Figure 5. Contours of 20% penetration depth for PAR as a function of chlorophyll and turbidity, with color fixed at 10mg Pt.l^{-1}. Calculations based on optical model for Chincoteague Bay and Rhode River, MD.

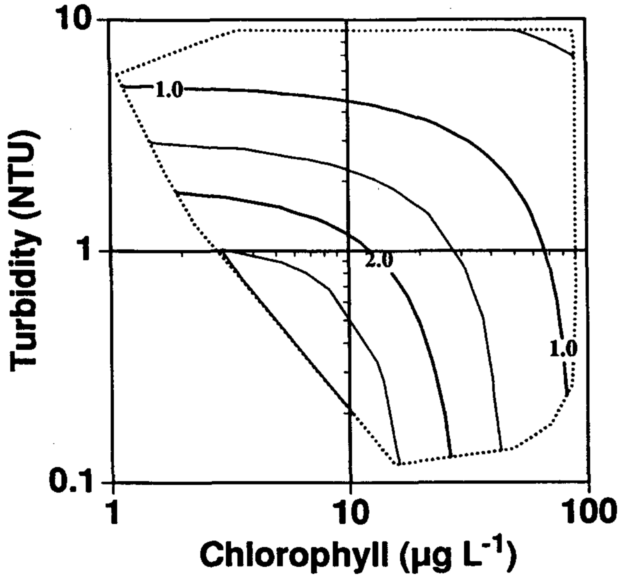
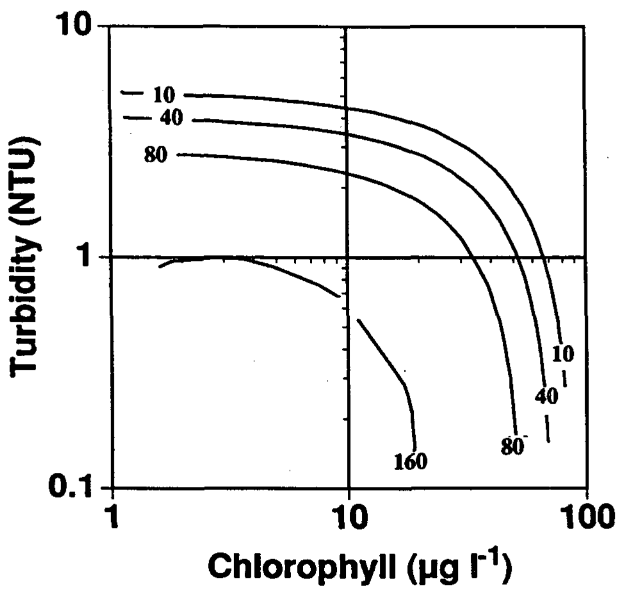


Figure 6. Sensitivity of the 1 meter 20% penetration depth for PAR as predicted by optical model for Chincoteague Bay and Rhode River, MD, to changes in color as a function of chlorophyll and turbidity. Labels on contours indicate value of color (mg Pt.l^{-1}), which was held constant as chlorophyll and turbidity were varied.



Use of inherent optical properties, which can be determined in the laboratory, to model diffuse attenuation coefficient based on the Monte Carlo studies of Kirk (1984) affords a great deal of flexibility to the approach taken here. The 20 percent penetration depth was chosen for illustration. If studies show that greater percentages of surface irradiance are required for colonization to greater depths, then that information can be easily accommodated. It must be emphasized, however, that the predictions are for water column attenuation only. The contours of Figure 5 indicate surprising tolerance to phytoplankton chlorophyll, and yet the effect of chlorophyll is properly included in the model (Figure 3b, 4b). It is likely that growth of epiphytes is secondarily correlated with conditions that would produce high chlorophyll in the water column. Determination of habitat requirements from observed plant distributions (Dennison *et al.*, 1993) would presumably be sensitive to any such correlations.

ACKNOWLEDGEMENTS

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THE ROLE OF EPIPHYTES IN SEAGRASS PRODUCTION AND SURVIVAL: MICROCOSM STUDIES AND SIMULATION MODELING[1]

by

Hilary A. Neckles, Ph.D.
U.S. Fish and Wildlife Service, National Wetlands Research Center
700 Cajundome Blvd.
Lafayette, LA 70506

Dr. Neckles is employed as a research ecologist with U.S. Fish & Wildlife Service in Lafayette, LA. Her research responsibilities focus on Gulf of Mexico systems, and currently include investigations of SAV-water quality relationships and the potential effects of global climate change in SAV habitats. She received a Ph.D. from the Virginia Institute of Marine Science in 1990 where she studied seagrass-epiphyte relations in *Zostera marina* ecosystems. Dr. Neckles received a M.S. from the University of Minnesota in 1984 studying the functional ecology of seasonally flooded prairie wetlands, and a B.S. from the University of Massachusetts in 1980.

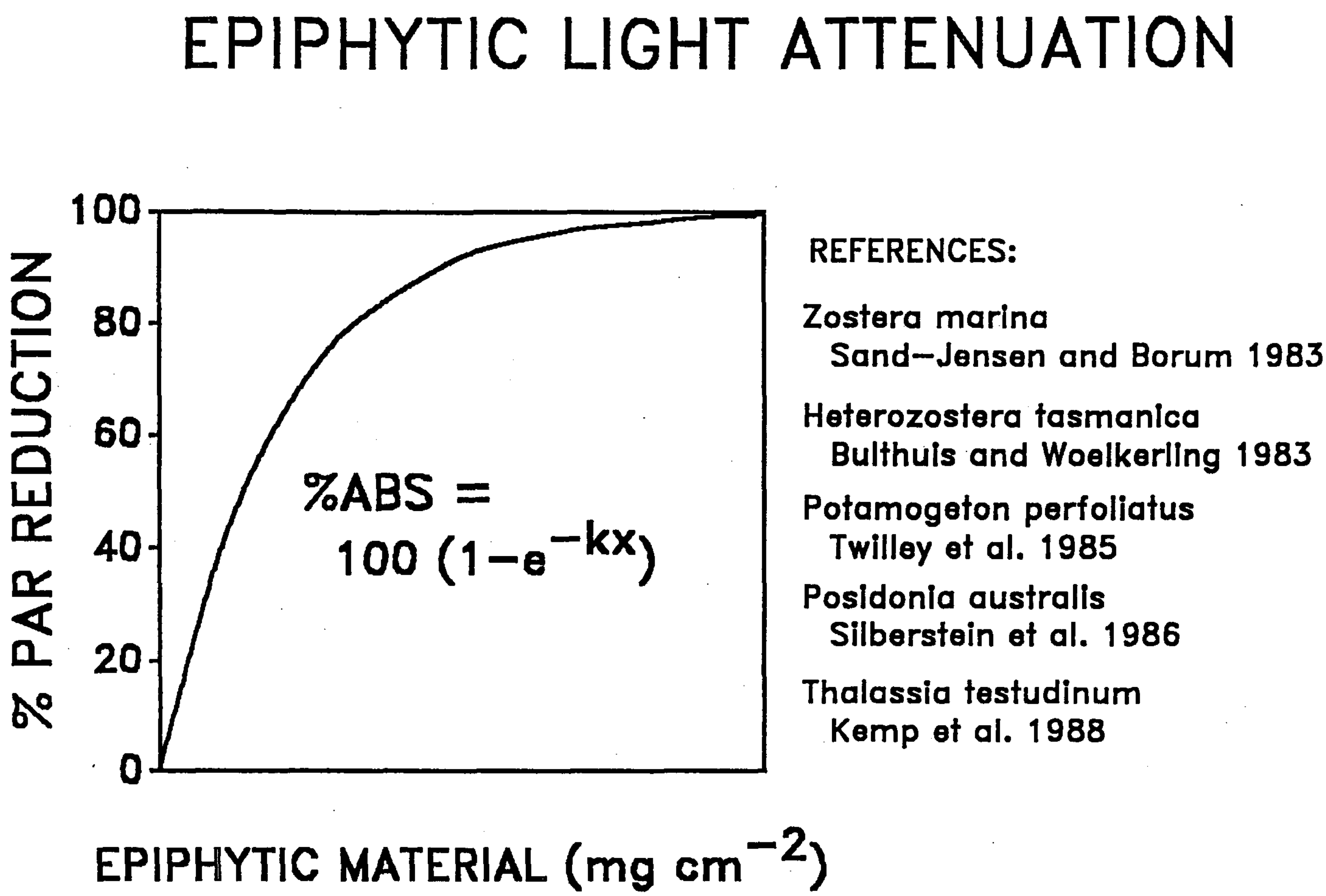
INTRODUCTION

This discussion will address some of the complex interactions controlling seagrass production and the use of simulation models to integrate this information for research and management purposes. Specifically, I will focus on the role of epiphytes in seagrass production and the development of one simulation model that incorporates epiphytes into predictions for seagrass survival.

Chuck Gallegos described how water quality constituents influence the submarine light environment. In modeling the ultimate response by seagrasses to light availability we need to consider also how water column light attenuation interacts with other potential environmental controls on plant growth, and how interspecific and temporal variability in physiological processes mediate plant response.

[1] The information presented here has been previously published in Neckles *et al.*, 1993; Neckles, 1990; and Wetzel and Neckles, 1986. Original sources should be cited.

Figure 1. Attenuation of PAR as a function of epiphyte density. k = epiphyte PAR attenuation coefficient ($cm^2\ mg^{-1}$).



Light transmitted through the water column to the seagrass canopy is attenuated further by an epiphyte matrix before reaching seagrass leaf surfaces. Epiphytes consist primarily of algae, bacteria, heterotrophic protozoans, and accumulated inorganic and organic substances. Studies in temperate and tropical submerged macrophyte communities have measured attenuation of photosynthetically active radiation (PAR) as an exponential function of epiphyte density (Figure 1). Thus a characteristic decay coefficient can be calculated for a given epiphyte community, analogous to the diffuse downwelling attenuation coefficient that describes the reduction of light through the water column. Attenuation at the leaf surface can then be predicted from the amount of epiphytic material present.

The effect of epiphytic light reduction on macrophyte photosynthesis will depend on the spectral selectivity of the epiphyte matrix. The wavelengths which are absorbed depend on the type of epiphytic material present. The data in Table 1 are from epiphytes of *Zostera marina* (eelgrass) in Chesapeake Bay. Epiphyte

Table 1. Spectral light attenuation coefficients for epiphytes of *Zostera marina,* Chesapeake Bay, April-June 1988.

Wavelength (nm)	Coefficient ($cm^2\ mg^{-1}$)
410	.45
441	.41
488	.36
507	.35
570	.28
589	.28
625	.27
656	.27
694	.26

Figure 2. *Zostera marina* grown under low nutrient concentrations with invertebrate grazers present. Epiphyte biomass is low.

Figure 3. High epiphyte biomass on *Zostera marina,* characteristic of growth at high nutrient concentrations or without the presence of invertebrate grazers.

attenuation coefficients were calculated for 10 nm bands across the photosynthetically active spectral range (400-700 nm). The epiphytic material is indeed spectrally selective; there is a higher attenuation at lower wavelengths. But epiphytes attenuate light across the range of PAR with no window of high transmittance. This shows the potential for epiphyte absorbance to reduce the light available for macrophyte photosynthesis.

The accrual of epiphyte biomass is regulated by diverse environmental variables, including nutrient supply, irradiance, grazing rates, temperature, and flow velocity. Several of these controlling factors are related either directly or indirectly to water quality. Nutrient supply, obviously, is a water quality variable; light is affected by water quality constituents; and grazing, although not traditionally addressed in terms of water quality, can be a function of dissolved oxygen concentrations, particularly in shallow areas.

These direct and indirect water quality variables can interact to control epiphyte biomass and consequent seagrass production. Figure 2 is a photograph of eelgrass from Chesapeake Bay grown in a controlled aquarium environment. Nutrient concentration was low and a population representing field densities of grazing invertebrates was present. Grown under these conditions the eelgrass leaves remain relatively free of epiphytes. Removing the grazer population or elevating the nutrient concentrations causes increased accrual of epiphyte biomass, as shown in Figure 3.

Variations in nutrient concentration and grazer densities occur on temporal and spatial scales. The relative magnitudes of these two variables will determine the ultimate effect on epiphyte biomass. In some cases grazing can prevent epiphyte accumulations, even under enriched conditions. Alternatively, if grazing invertebrates are less active or at low population densities they may not keep pace with accelerated epiphyte growth due to nutrient enrichment.

How does this affect macrophyte growth? Figure 4 shows epiphyte biomass and macrophyte production under various combinations of nutrient enrichment and grazing (from Neckles *et al.*, 1993). These treatments were applied in microcosms designed to simulate eelgrass habitat in Chesapeake Bay. Grazer densities during early summer are moderate, and the level of nutrient enrichment (3X ambient concentrations) is characteristic of sites in Chesapeake Bay from which eelgrass has declined. Experimental conditions of ambient nutrient concentrations with grazers

Figure 4. Epiphyte and macrophyte responses to nutrient and grazer treatments applied to *Zostera marina* microcosms in early summer (June-July), Chesapeake Bay (Neckles *et al.*, 1983).

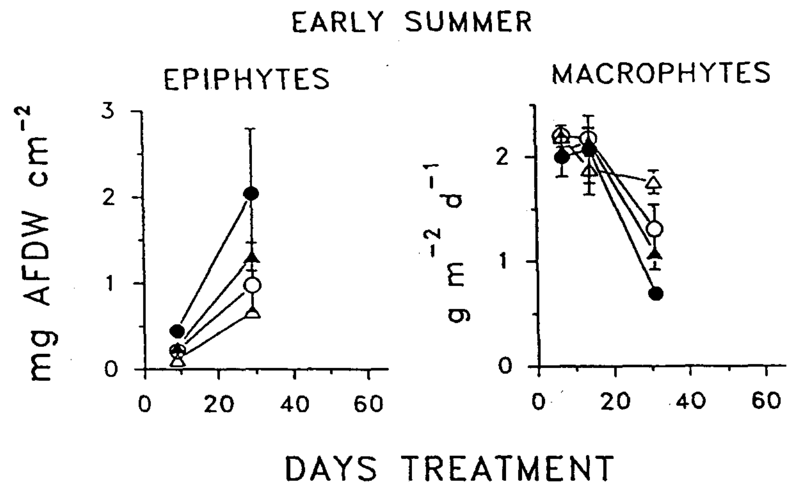
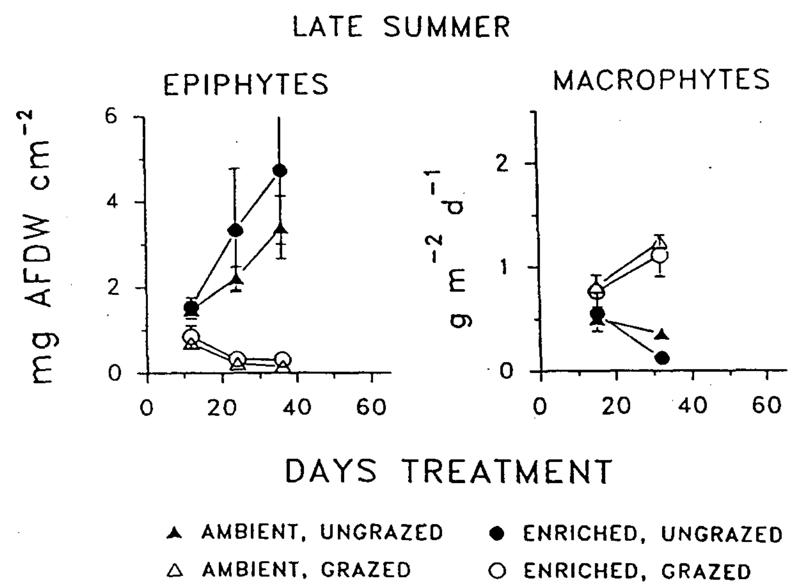


Figure 5. Epiphyte and macrophyte responses to nutrient and grazer treatments applied to *Zostera marina* microcosms in late summer (August-September), Chesapeake Bay (Neckles *et al.*, 1983).



present (open triangles) represent sites in Chesapeake Bay with historically stable eelgrass communities. Either grazer removal (difference between open and solid symbols) or nutrient enrichment (difference between triangles and circles) increases epiphyte biomass consistently, such that the greatest biomass occurs under enriched conditions with grazers absent (solid circles). The pattern of epiphyte biomass is mirrored by macrophyte growth; the greatest macrophyte production occurs under conditions promoting the least epiphyte biomass.

At the higher grazer densities characteristic of late summer, however, epiphytes cannot "outrun" grazing, even under nutrient enriched conditions (Figure 5). As long as grazers are present, epiphyte biomass remains very low and macrophyte production is correspondingly high. Thus macrophyte responses to water quality variables can vary with the severity of environmental controls.

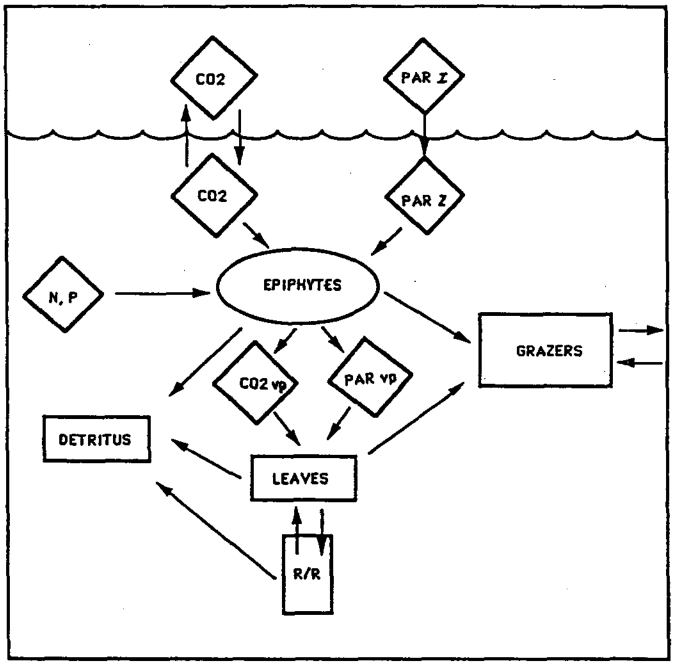
Epiphyte biomass can also influence macrophyte responses to light availability. Studies in temperate (Moore *et al.*, 1989) and tropical (Tomasko and Lapointe, 1991) seagrass systems have shown an increase in light availability to favor epiphyte growth more than macrophyte growth. Such a response would be expected particularly in nutrient enriched environments.

SIMULATION MODEL STUDIES FOR *Zostera marina* IN CHESAPEAKE BAY

Simulation models offer a means to integrate complex interactions among ecosystem components and to predict long-term system behavior. At the very least, modeling can provide a conceptual framework for linkages among system components. This exercise alone can identify gaps in our understanding of ecosystem function. More importantly for the purposes of this symposium, modeling offers a liaison between science and management and can be applied effectively as a management tool.

The following model was developed originally by Dick Wetzel for eelgrass in Chesapeake Bay. Details of model structure and simulation studies appear in Wetzel and Neckles (1986) and Neckles (1990). The model simulates the flow of carbon through eelgrass community components, under control of what are believed to be the most important physical forcing functions and biological interactions of the system (Figure 6). Briefly, eelgrass productivity is dependent on the availability of dissolved carbon and light. Carbon is replenished from the atmosphere and does not become limiting, whereas light, as PAR, is attenuated through the water column before reaching the macrophyte canopy. Therefore, reductions in water transparency

Figure 6. Conceptual model of the *Zostera marina* community.



can limit light availability at the canopy depth, depicted as PAR at depth z. An epiphyte matrix further reduces light transmittance and carbon diffusion to leaf surfaces. Epiphyte biomass accumulates through microalgal photosynthesis, and is enhanced by increases in dissolved nutrient concentrations. Epiphytes are removed by grazing invertebrates. Other physical controls included in the model are photoperiod and water temperature. All biological components lose carbon through respiration and natural mortality. Growth of biological components is regulated by density dependent feedback functions.

Initial conditions for model simulation are characteristic of stable eelgrass habitat in Chesapeake Bay. The model-predicted annual pattern of leaf biomass accumulation is depicted by the solid line in Figure 7, in comparison with field data from historically stable eelgrass beds (each symbol represents a different site). Although the predicted and observed curves are out of phase the predicted annual maximum standing stock and the pattern of biomass accumulation agree with available data, suggesting that the model is a suitable tool for interpreting long-term responses to environmental change.

Figure 7. Annual pattern of *Zostera marina* leaf biomass accumulation predicted by the simulation model (solid line) and observed at 5 sites in lower Chesapeake Bay (symbols; from Wetzel and Neckles, 1986).

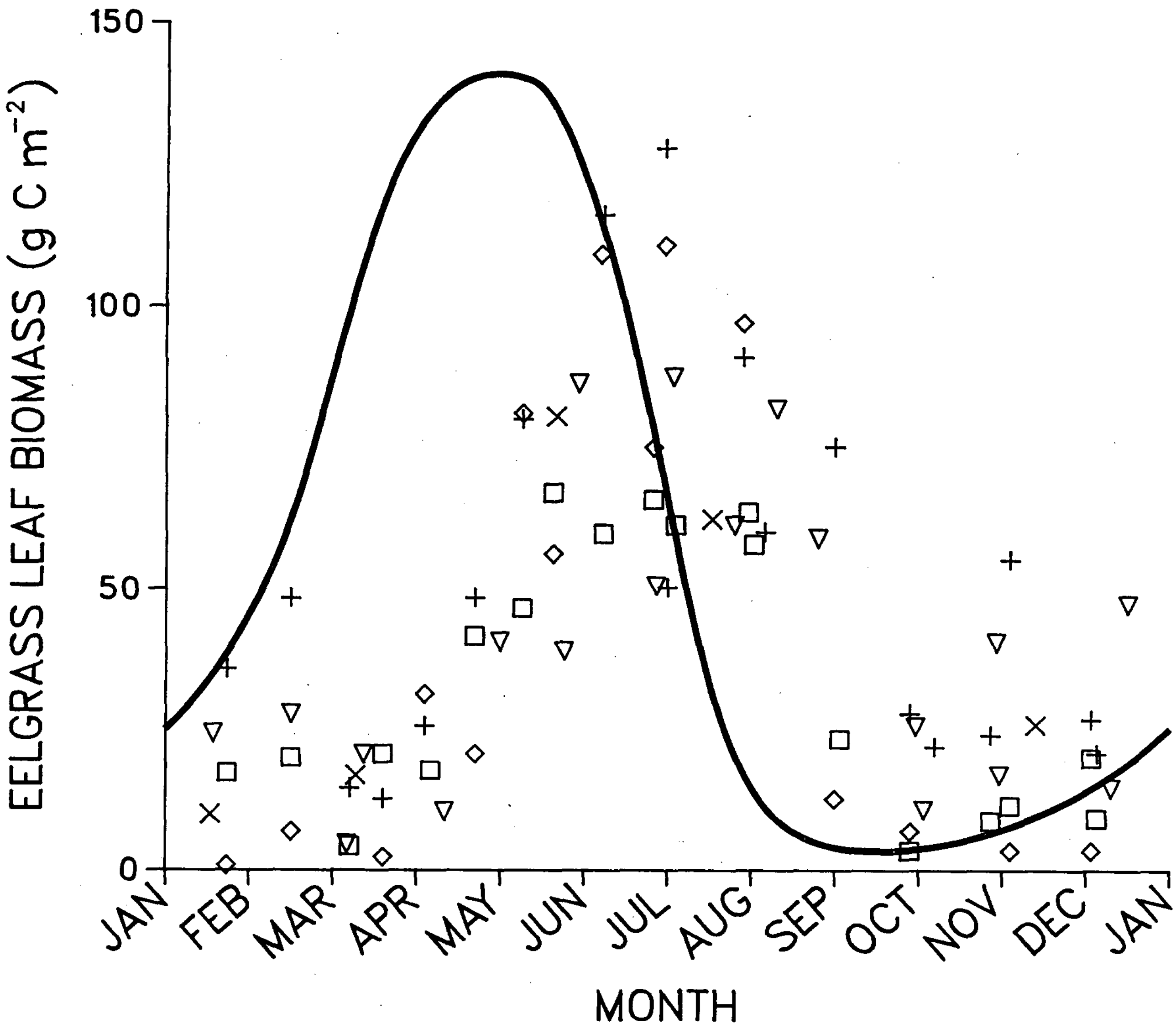


Table 2. Model-predicted annual maximum leaf biomass (g C m^{-2}).

Grazing	k	Ambient Nutrients	Enriched Nutrients
Present	1.00	141	96
	1.25	136	104
	1.50	107	*
Absent	1.00	105	*
	1.25	53	*
	1.50	*	*

We can use the model to predict eelgrass community response to environmental change, or, conversely, to suggest the levels of environmental variables necessary to ensure eelgrass survival. Table 2 shows the results of 10-year model simulations under various combinations of environmental controls. Ambient nutrient concentrations represent conditions at sites in Chesapeake Bay which currently support eelgrass growth, and enriched concentrations represent conditions at sites from which eelgrass has disappeared. Numbers indicate the stable annual maximum leaf standing stocks (g C m^{-2}) attained during a simulation, and asterisks indicate loss of the community. We see that if light attenuation alone is increased from an attenuation coefficient of 1.0 to 1.5, annual standing stocks are reduced. This degree of light reduction in conjunction with nutrient enrichment or a loss of grazers, however, causes loss of the community. Similarly, nutrient enrichment alone will not cause loss of the community, but does cause increased susceptibility to light reduction or a loss of grazers. Models such as the example shown here can thus help interpret community responses to multiple environmental changes.

Table 3. Biological processes included in the *Zostera marina* simulation model.

Zostera marina	
	Photosynthesis
	Respiration
	Translocation
	Mortality
Epiphytes	
	Photosyntheses
	Respiration
	Mortality
Grazers	
	Ingestion
	Assimilation
	Respiration
	Emigration/predation
	Recruitment

What data are required to build this type of model? First, a minimum set of processes which describes system function must be identified. The biological processes included in the model are listed in Table 3. The model is constructed of equations which define the relationships among system components in terms of these biological processes. Biological processes are defined mathematically as functions of specific rate coefficients. These coefficients are measurable parameters for which, very often, literature values already exist. The biological processes in the eelgrass model are defined in term of the parameters listed in Table 4. Table entries indicate rate coefficients for the transfer of carbon from donor to recipient compartments. Many processes are modeled as simple linear functions of the rate coefficient and the donor compartment size. Those coefficients in Table 4 without asterisks are used in

Table 4. *Zostera marina* simulation model minimum data requirements: biological interactions. Table entries are rate coefficients for transfer of carbon from donor to recipient compartments. Asterisks indicate that coefficient is used in nonlinear, feedback controlled function; coefficients without asterisks are used in simple linear functions.

Donor	Recipient				
	Environment	Leaves	Root/rhizome	Epiphyte	Grazer
Environment		Photosynthesis*		Photosynthesis*	Birth Immigration
Leaves	Respiration Mortality		Translocation*		Ingestion*
Root/Rhizome	Respiration Mortality	Translocation*			
Epiphyte	Respiration Mortality				Ingestion*
Grazer	Egestion Respiration Mortality Predation				

such linear equations. Other processes are more realistically described by nonlinear, feedback-controlled functions. Transfer functions based on rate coefficients with asterisks in Table 4 are mediated by feedback terms. Changes in any compartment size are simply the sum of inputs minus the sum of outputs for any time interval. For example, changes in leaf biomass equal gains from photosynthesis minus losses from respiration, mortality, translocation, and ingestion by grazers.

Physical forces can be included in the model as controls on rate coefficients. The physical variables included in the eelgrass model are listed in Table 5. For example, the photosynthetic rate coefficients are dependent on temperature and light. Environmental variability can be incorporated as temporal changes in physical variables.

Table 5. *Zostera marina* simulation model minimum data requirements: physical variables.

Variable	Units
Temperature	°C
Solar insolation	$E\ m^{-2}\ d^{-1}$
Water depth	m
PAR attenuation	m^{-1}
Photoperiod	h
Inorganic nutrients	µM

I have attempted to describe how simulation models can be constructed from measurable parameters using realistic functional relationships. Modeling exercises can improve our understanding of system function and identify future research needs. The results of simulation studies can also help guide management decisions. Ideally, modeling can serve as a two-way conduit between research and applications to meet conservation needs.

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SAVI SECTION 5:

MANAGEMENT OF THE INDIAN RIVER LAGOON

DEVELOPMENT AND OPERATION OF THE INDIAN RIVER LAGOON WATER QUALITY MONITORING NETWORK

by

John Higman
St. Johns River Water Management District
P.O. Box 1429
Palatka, FL 32178-1429

John Higman is an Environmental Specialist III with the St. Johns River Water Management District. He is manager of the Indian River Lagoon water and sediment program, and project manager of the Indian River Lagoon Water Quality Monitoring Network. Mr. Higman received his B.S. in zoology and M.S. in environmental engineering sciences from the University of Florida. He has authored and co-authored numerous publications dealing with nutrient dynamics, water chemistry, and hydrology.

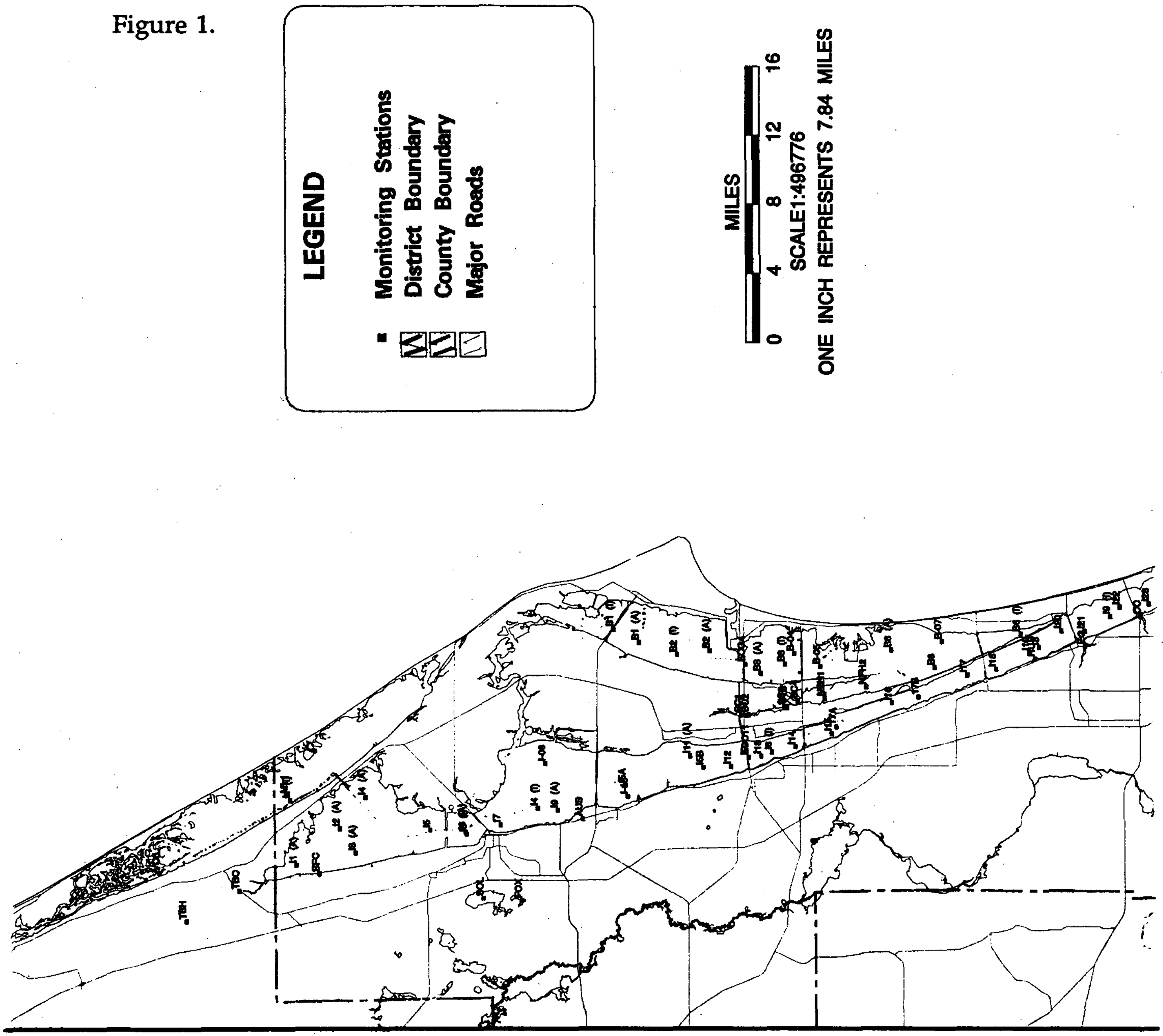
INTRODUCTION

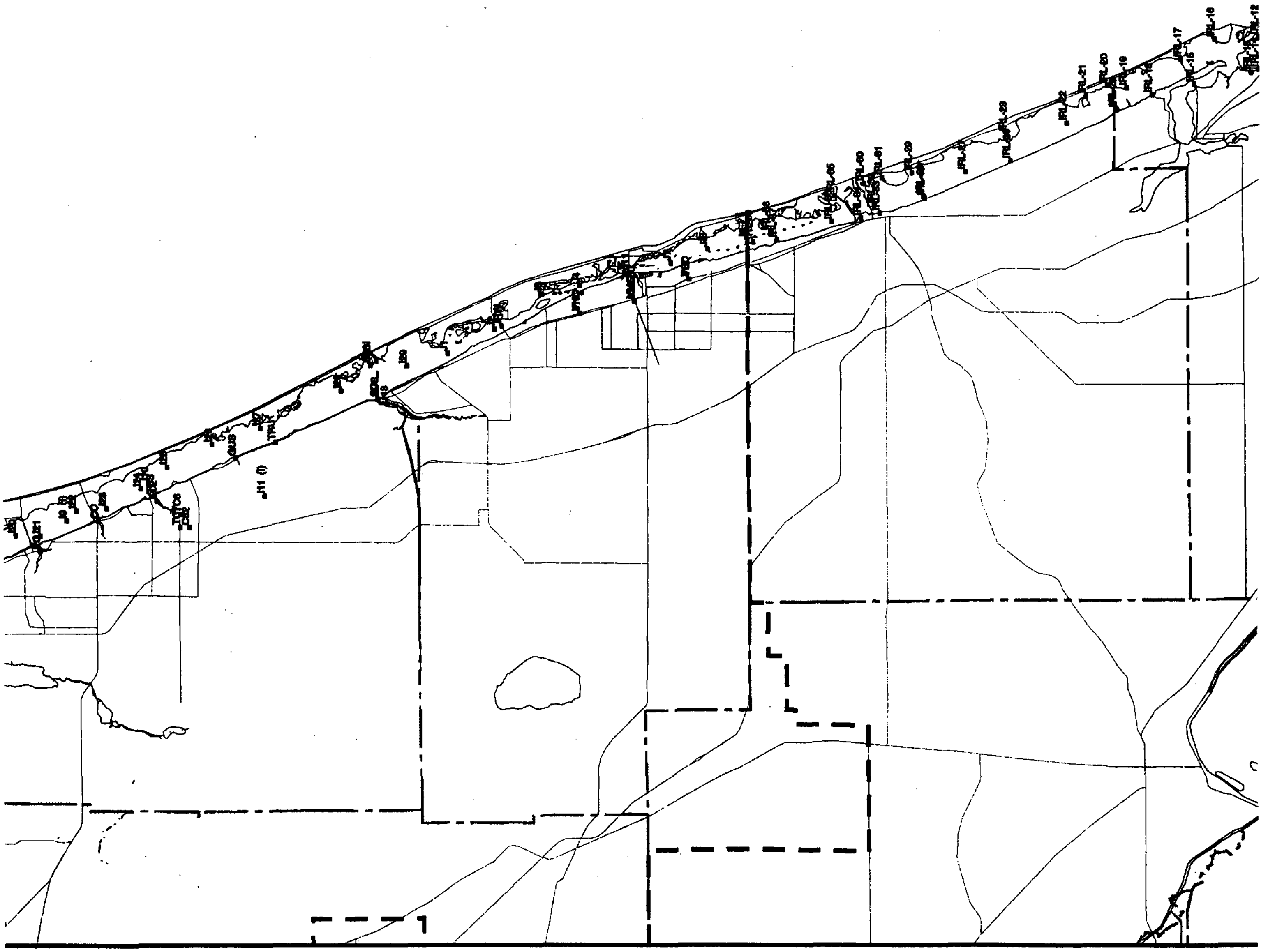
The Indian River Lagoon Water Quality Monitoring Network (IRL-WQMN) is a cooperative, multi-agency program designed to accurately depict the physical and chemical conditions of the water quality in the Indian River Lagoon. Current WQMN participants include:

* Brevard County Office of Natural Resource Management
* Florida Department of Environmental Regulation
* Indian River County Public Health Unit
* St. Johns River Water Management District
* South Florida Water Management District
* Volusia County Environmental Resource Management

The participants have agreed to standardize sampling dates, parameters, and chemical analyses so that the data are consistent. The lagoon is sampled in 135 sites (Figure 1) at least on a quarterly basis. These sites have been sampled since 1989.

Figure 1.


LEGEND
Monitoring Stations
District Boundary
County Boundary
Major Roads
MILES
0 4 8 12 16
SCALE1:496776
ONE INCH REPRESENTS 7.84 MILES



The physical parameters that are sampled include:

* water and air temperature,
* meteorological data (wind direction, speed, cloud cover),
* depth measurements of sample and site,
* salinity and conductivity,
* Ph,
* dissolved oxygen,
* secchi disc measurements,
* photosynthetic active radiation (PAR); measured at 5 different depths (or more).

The chemical parameters include:

* total suspended solids (TSS),
* color,
* turbidity,
* total phosphorus,
* ortho-phosphorus (soluble reactive),
* total Kjeldahl nitrogen,
* nitrate/nitrite,
* chlorophyll a, b, c, and pheophytin.

Quality assurance procedures have been published in a Water Quality Assurance/Quality Control Manual (Steward and Higman, 1991). This manual describes the WQMN standard operating and quality control procedures, and in addition, contains each of the individual participants QA/QC plans. Quality control split samples are taken each quarter and analyzed to quantify the variability among participating laboratories.

Water quality monitoring is mandated by federal and state legislation. Some of the federal legislation concerning water quality published in the Clean Water Act (Code of federal regulations, 1990) is listed in Table 1.

Table 1.

FEDERAL TITLE 33 AND 40

TITLE 33 USC-1251 et seq.

FEDERAL WATER POLLUTION CONTROL ACT

33-1311	Effluent limitations (h-3 monitoring impacts)
33-1312	Water quality related effluent limitations
33-1313	Water quality standards and implementation plans
33-1316	National standards and performance
33-1319	State enforcement; Compliance orders
33-1329	Non-point source management programs
33-1330	National estuary program (NEP)
33-1341	Certification (permit issuance criteria)
13-1342	National pollution discharge elimination system (NPDES) including technology based effluent limitations (TBELS) and total maximum daily loads (TMDLS)

TITLE 40 CFR

PROTECTION OF THE ENVIRONMENT

40-122	Administered permit programs: NPDES
40-123	State program requirements
40-125	Criteria and standards for the NPDES

Table 2.

Chapter 17 F.A.C. and Chapter 373 and 403 F.S.

17-25	Regulation of storm water discharge * 80% annual average pollutant load reduction * 95% annual average pollutant load reduction for those systems discharging into outstanding Florida waters
17-302	Anti-degradation policy for surface water quality
17-40	State water policy
17-40-.420	Surface water protection and management (PLRG)
17-601	Domestic waste water treatment plant monitoring

The Florida DEP, in addition to federal mandates, also has water quality responsibilities (Florida administrative codes, 1993; and Florida Statutes, 1993). Some of these responsibilities that require water quality monitoring are listed in Table 2, including the newest legislation that requires development of pollution load reduction goals (PLRG).

Although much of the water quality legislation falls within the jurisdiction of the state, no state agency closely monitors the water quality of all surface waters. Consequently, a large amount of compliance monitoring becomes the counties responsibility. For example, the local county environmental resources or health agencies, by necessity, must respond more rapidly to local pollution problems than would the EPA or DEP. Therefore local county environmental and health department water quality monitoring programs need to be supported by federal and state agencies.

Through the SWIM program the water management districts have supported and contributed to the improvement of the local county water quality programs. This IRL-WQMN helps fulfill some of the water management district goals and objectives described in the Indian River Lagoon Surface Water Improvement and Management (IRL SWIM) plan (Table 3).

Table 3.

IRL SWIM GOALS

I. "To attain and maintain water and sediments of sufficient quality ("...to Class III or better...") in order to support a healthy macrophyte based, estuarine lagoon system.

Objective A. Management of fresh water inflows...
Objective B. Assessment of suspended matter loads...
Objective C. Reduction of point and non-point source loadings...

The main objective of the WQMN effort is to collect long term data that would be used to:

1) identify point and non-point pollution source problem areas,
2) document long-term trends in lagoon water quality, and
3) provide supplementary information for other management decisions.

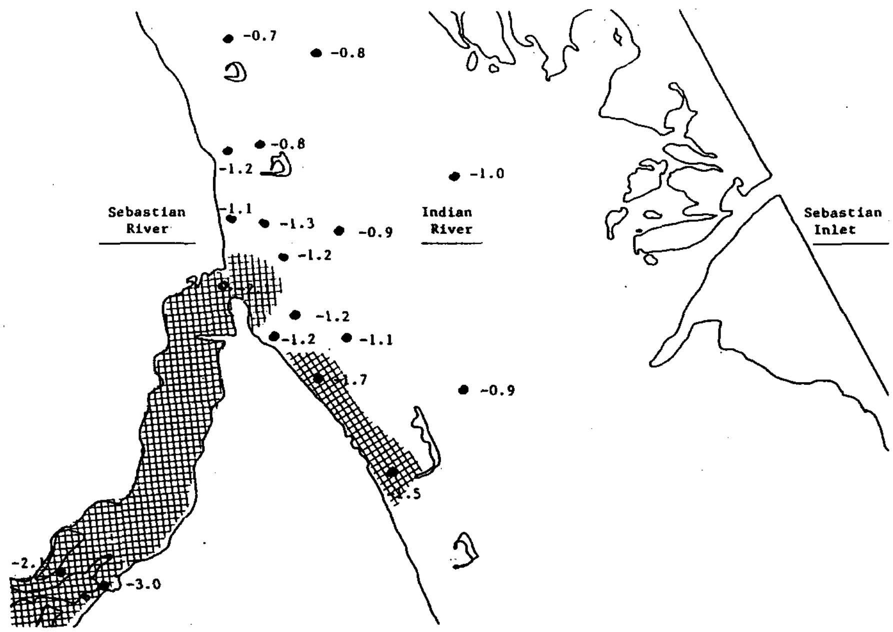
Data from the IRL-WQMN can be used in the SAV Initiative. For example, to quantify the affects of surface water runoff on light attenuation in the Indian River, light measurements were made during the 1991 summer rainy season. Light attenuation values measured in July after 250,000 cubic meters and in August after 350,000 cubic meters of fresh water had flowed in to the Indian River are shown in Figures 2 and 3, respectively. The extent and effect of the highly colored fresh water plumes are indicated by the calculated light attenuation coefficients (*K* values) shown in these two Figures. A comparison of the light attenuation coefficients less than or equal to -1.5 demonstrates that the fresh water plume increased in extent and shifted position during the week between the two sampling episodes. These data and additional data like these will contribute to our understanding of the effects large volumes of fresh water have on estuaries. This knowledge can be used by water managers to minimize the detrimental influences of fresh water discharges on estuarine systems.

The IRL-WQMN is a Lagoon-wide, coordinated, cohesive, and technically sound water quality monitoring program that requires the participation of federal, state, regional and local agencies. Through cooperation the participating agencies are able to obtain water quality information that accurately describes the physical and chemical conditions in the Indian River Lagoon. Photosynthetically active radiation is one parameter that is measured at least quarterly at 135 sites in the Indian River Lagoon. Water quality monitoring is mandated by current federal and state legislation, and regional and local agencies need accurate water quality information to make informed management decisions. In addition, water quality monitoring network participants are willing to cooperate with and supplement the National Estuary Program's IRL submerged aquatic vegetation initiative.

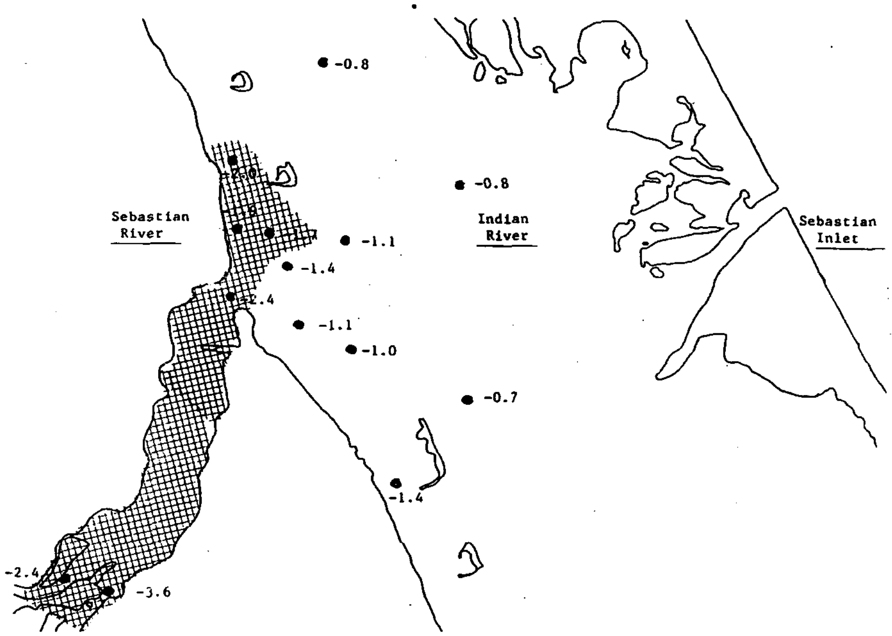
Figure 2 and 3. Light Attenuation in Sebastian River and Adjacent Indian River Lagoon

- * K values for each station are averaged throughout the entire water column and are based on three replicate profiles.

JULY 25, 1991



AUGUST 7, 1991



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EXAMPLES OF WATERSHED PROJECTS IN THE INDIAN RIVER LAGOON

SURFACE WATER IMPROVEMENT AND MANAGEMENT (SWIM) PROGRAM

by

Joel Steward
St. Johns River Water Management District
P.O. Box 1429
Palatka, FL 32178-1429

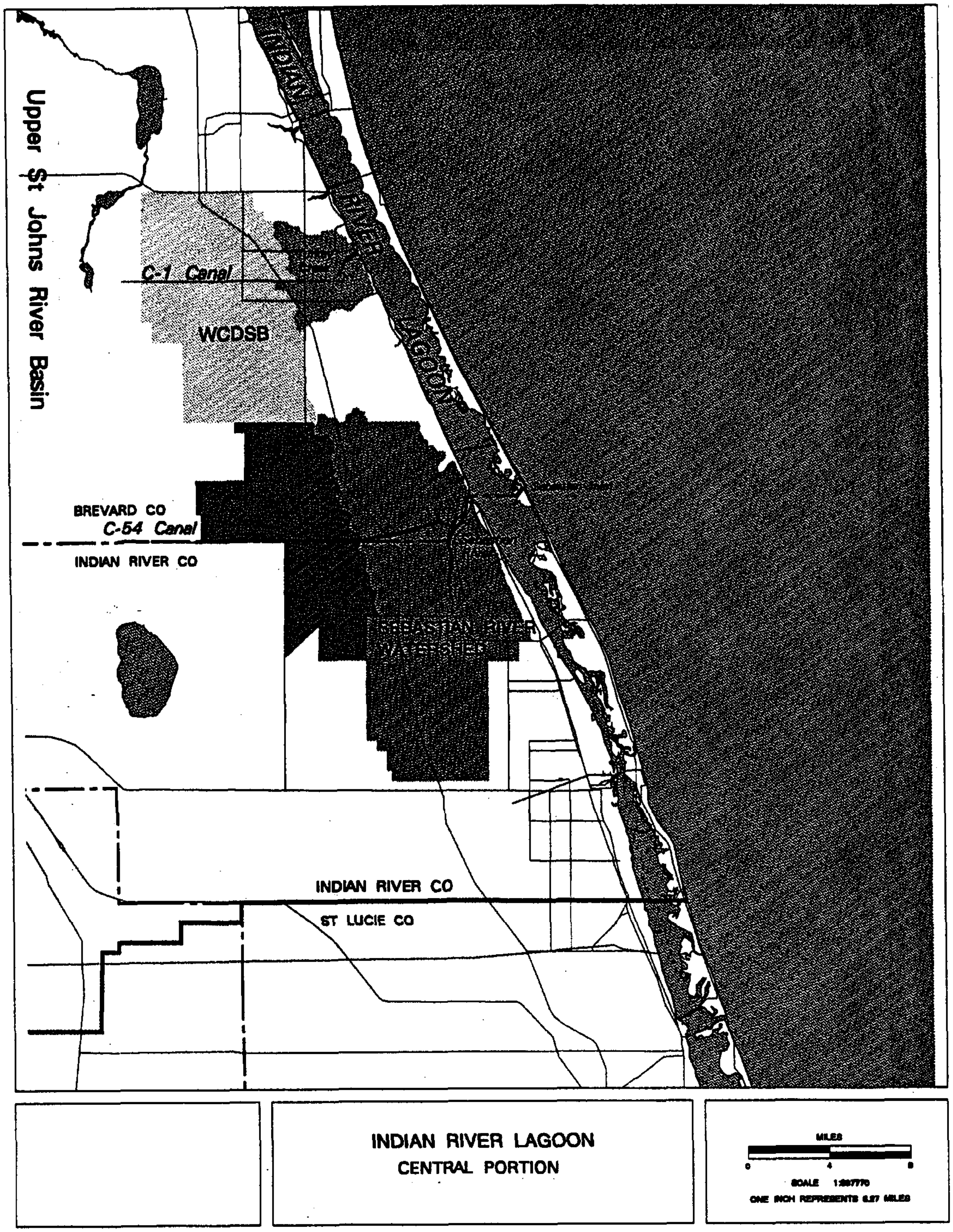
Joel Steward is the Technical Program Manager of the Coastal Basins section, Division of Environmental Sciences at the St. Johns River Water Management District. Mr. Steward received his B.S. in biology from the College of William & Mary in Virginia and an M.S. in bio-environmental oceanography from the Florida Institute of Technology.

INTRODUCTION

A basic management philosophy of the St. Johns River Water Management and the South Florida Water Management Districts (SJRWMD and SFWMD) is the utilization of the watershed perspective in the development of water resource protection strategies. This is, apparently, a shared philosophy of the National Estuary program and the SWIM program of the SJRWMD and SFWMD. Furthermore, mutual goals in the management of the Lagoons system -- attainment and maintenance of a macrophyte-based system of productivity, including seagrasses -- will enable IRLNEP and SWIM to achieve a unified management plan in the next five years.

In pursuing a watershed management approach for the diagnosis and remediation of resource problems, the 2,283 square mile area of the IRL basin was subdivided into sub-basin management units. A prioritization process, based on several criteria (including degree of water quality and habitat degradation, public use importance, etc.), identified sub-basins that will receive immediate attention. Two of the these critical priority sub-basins are the Turkey Creek and Sebastian River watersheds (Figure 1).

Figure 1.


Upper St Johns River Basin
C-1 Canal
WCDSB
BREVARD CO
C-54 Canal
INDIAN RIVER CO
SEBASTIAN RIVER WATERSHED
INDIAN RIVER LAGOON
INDIAN RIVER CO
ST LUCIE CO
INDIAN RIVER LAGOON
CENTRAL PORTION

OVERVIEW OF INVESTIGATIVE AND MANAGEMENT STRATEGIES

The Turkey Creek watershed is approximately 114 square miles in area and Sebastian River is 170 square miles. They are two of the largest tributary watersheds in the Lagoon basin. Most of the land area within these watersheds was historically within the floodplain of the upper St. Johns River basin. Inter-basin drainage diversion projects, at the beginning of the 20th century, for the purpose of expanding agricultural production, enlarged these coastal watersheds by an order of magnitude. Since the 1960s, land-use in the Turkey Creek watershed has gradually converted from agricultural to predominantly urban. Whereas the Sebastian River watershed has remained predominantly agricultural. The hydrology of both watersheds has been tremendously altered, presumably impacting the water quality and ecology of the receiving waters in Turkey Creek, Sebastian River, and the Indian River Lagoon. The timing, volume, discharge rates, and quality of freshwater drainage conveyed by large inter-basin diversion canals are the main issues being addressed in these watersheds. The primary canals are Canal 1 (C-1) that drains into Turkey Creek, and Canal 54 (C-54) that drains into the North Prong of the Sebastian River.

There are three fundamental steps used to develop watershed resource plans:

- **Diagnosis:** Identification of the real problems, their extent and sources;
- **Feasibility:** Examination of alternatives that control the problems at the sources or as close to the sources as possible;
- **Management:** Implementation of the best alternative(s) and other prescribed solutions.

The identification of the issues or problems has been a decade-long process that included a series of symposia, the establishment of state-appointed committees, a SWIM technical advisory group, and currently the NEP planning conference. Some of the Lagoon's identified problems include nutrient over-enrichment, excessive loadings of total suspended matter, an increased rate of muck sedimentation, and seagrass decline. It was also recognized that all of these problems are inter-related and thus so should be the diagnostic strategies.

In an attempt to address some of the issues in an integrated fashion, the SJRWMD is conducting a diagnosis of freshwater discharge impacts on the Lagoon ecology and economy. Diagnostic investigations centered on freshwater discharge impacts should lead managers to a major part of the problem and thus the development of specific solutions concerning altered salinity regimes and excessive nutrient and suspended matter loadings.

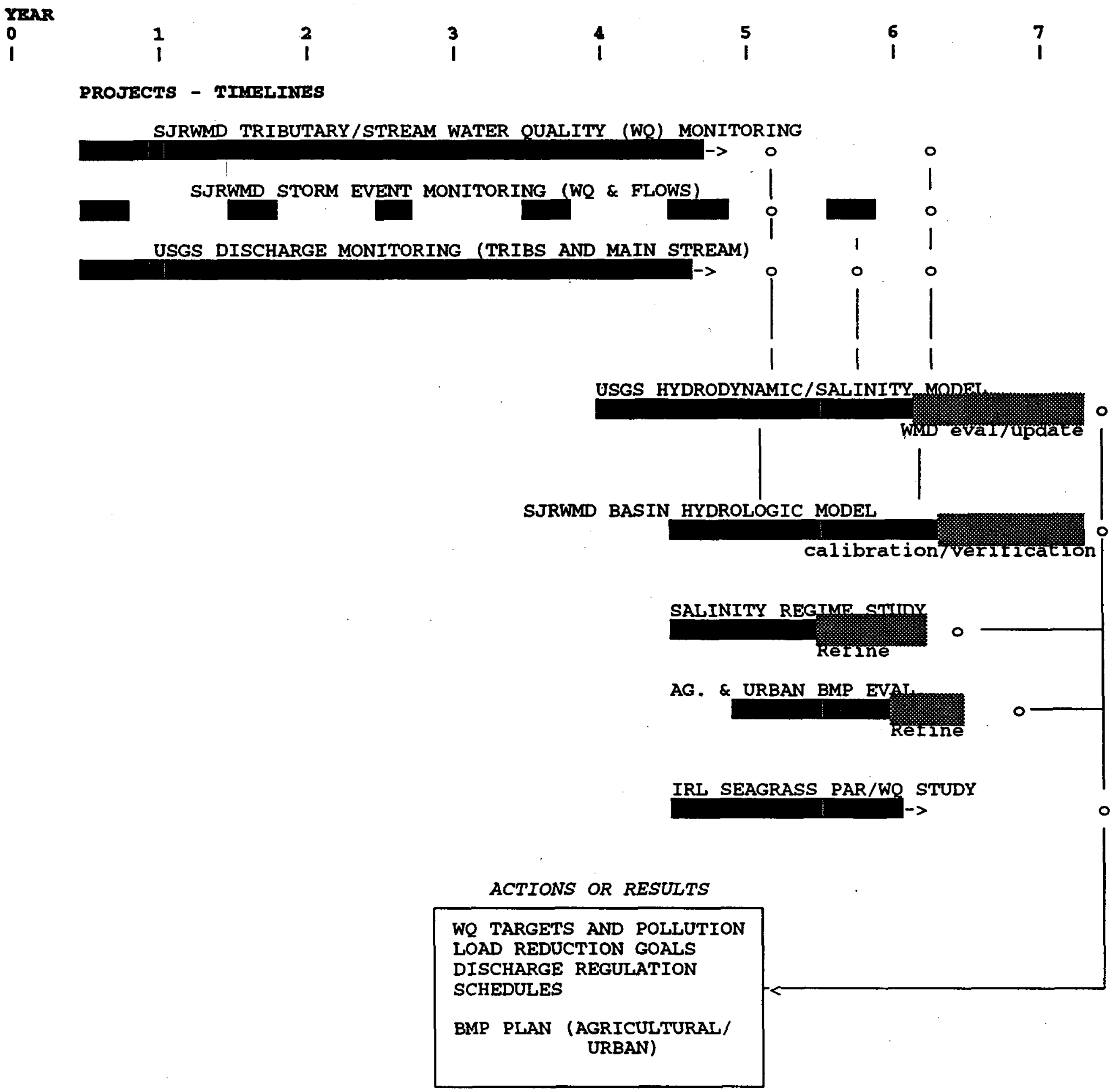
A data collection phase is, of course, a prerequisite to management planning. Water quality monitoring, hydrologic modeling (e.g. rainfall/discharge relationships) and hydrodynamics and salinity modeling are some of the projects underway. The monitoring efforts generate the data for the calibration of deterministic models and analysis of discharge effects on flood potential, shoreline erosion, salinity, etc. These analyses help develop desirable freshwater discharge schedules for canals such as C-1 and C-54.

Evaluation of salinity regime (temporal and spatial), and the extent of impact caused by freshwater inputs, was initially based on the Lagoon's hard clam fishery (*Mercenaria* spp.). This is an important fishery in the Lagoon near the Turkey Creek and Sebastian River watersheds. Incipient salinity standards were established based on the larval hard clam's sensitivity to salinity fluctuations. This was followed by recommended maximum discharge limits that would help maintain salinities accordingly. Further assessments of the hydrologic-salinity regime relationship based on more comprehensive ecological criteria (e.g., macrophyte communities, other species of special concern) are being evaluated to refine discharge schedules for C-1 and C-54. (In the case of C-1, recommended maximum discharge limits were also based on downstream shoreline erosion and flood potential.)

Following a "first cut" evaluation and development of a salinity-based freshwater inflow schedule, refinement of the schedule may be necessary to manage the inputs of suspended matter and nutrients. However, the most effective management of these loadings would be source control, such as the implementation of agricultural Best Management Practices (BMPs). The degree to which these constituent loadings should be controlled depends on pollutant load reduction targets intended to help meet ecological restoration goals. For the Indian River Lagoon, an important ecological goal involves the widespread coverage of healthy, functional seagrasses. It is becoming increasingly clear that excessive suspended matter and nutrient loadings and concentrations can place tremendous stress on seagrasses by limiting light availability.

The relative sequence of projects and their inter-dependency in the context of watershed management programs can be shown in the generic watershed project

Table 1.
General Timelines and Critical Path for Watershed Projects



timeline (Table 1). The SJRWMD is conducting these projects with assistance form private consultants, state agencies, U.S. Geological Survey, water control districts, counties and municipalities.

PROPOSED MANAGEMENT STRATEGIES IN THE TURKEY CREEK WATERSHED

Investigations in the Turkey Creek watershed have progressed farther than in Sebastian. Preliminary assessments and recommendations are completed with respect to the control of freshwater discharges from C-1 to Turkey Creek. It was found that 500 to 1,000 cubic feet/second (cfs) of discharge can lower the Lagoon's salinity to below 20ppt within 500 meters from the mouth of Turkey Creek (depending on antecedent salinity levels). Such discharges have the potential of significantly increasing the mortality of hard claim larvae during the spawning seasons of spring and fall. It was also found that erosion of critical shoreline areas became significant when discharges exceeded 1,000 cfs; and at that rate, sediment loadings to Turkey Creek are 50 times that at base flow rates (<150 cfs). As a result, it is recommended that a maximum discharge of 1,000 cfs be followed during the summer and winter months and a maximum of 700 cfs in the spring and fall. Such reductions in peak rates of discharge will also serve to limit the rate of muck sediment deposition in the mouth of Turkey Creek.

Despite the fact that we have not yet established resource-based (seagrass) nutrient and suspended matter load reduction targets, the SJRWMD and local cooperators (primarily the Water Control District of South Brevard and the City of Palm Bay) are currently pursuing watershed initiatives to reduce loadings (Table 2). The SJRWMD has tentatively established C-1 annual pollutant load reductions for nutrient and suspended matter by 80 percent on an annual average. It is also recommended that a C-1 discharge schedule address minimum freshwater allocations to Turkey Creek as well as maximum allowable discharges.

One of the major initiatives in the Turkey Creek basin involves a project, presently in the conceptual planning phase, to re-divert C-1 drainage from Turkey Creek to the St. Johns River marsh (Table 2). Accomplishment of this initiative would mean substantial progress toward achieving the recommended reductions in freshwater discharges and pollutant loadings. The ultimate, intended result of these actions is the recovery of seagrasses in the central Lagoon.

Table 2.
Turkey Creek & Water Control District of South Brevard Comprehensive Watershed Management Plan

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Targets

- Reduce maximum C-1 discharge (~ 700 cfs)
- Reduce C-1 annual pollutant loads (by 80%)
- Establish minimum C-1 discharge
- MUCK -- establish limits on depositional rates, sediment loadings
- Establish other water quality targets

Initiatives

- Re-diversion of C-1 drainage away from Turkey Creek and to the St. Johns River basin
- Regulatory measures: stormwater and erosion control
- Retrofit drainageways
- C-1 discharge schedule
- MUCK removal
- Management of erosion prone areas, septic tank problem areas, sources of toxic substances

SAVI IMPLEMENTATION PROJECTS, PROPOSED BUDGET AND TIMELINE

Robert Day
Indian River Lagoon National Estuary Program
1900 South Harbor City Boulevard
Suite 109
Melbourne, FL 32901-4749

Robert Day currently serves as the Project Scientist for the Indian River Lagoon National Estuary Program. He received his B.S. in biology from the Florida Technological University (now known as University of Central Florida) in Orlando in 1976. Since then, he worked for the Florida Department of Environmental Regulation and the Brevard County Division of Natural Resources as a environmental specialist involved in the monitoring and management of natural resources in the Indian River Lagoon.

INTRODUCTION

I would like to discuss a proposed schedule for the projects, and how they are a part of the Submerged Aquatic Vegetation Initiative.

The following schedule is a "goal", an ideal schedule that, if everything in the world were perfect, we would be able to accomplish on time and on budget. Understanding that the world we live in is less than perfect, IRLNEP and SWIM will work with the existing programs to meet this schedule as best we can.

The comments we hope to receive concern the elements of the program. Specifically, will this proposed program develop the information needed to support a modeling effort? Can this program provide adequate information to monitor the effectiveness of demonstration projects or strategies implemented to address identified problems? Finally, is the sequence of the projects appropriate?

There are several items included in Appendix I concerning projects to implement the SAVI. The project task outline and project timetable is a "fleshed out" version of the timetable with participating agencies and estimated costs listed. The third item, the project schedule, offers more description of the projects and what they are intended to accomplish.

You will note that the projects generally fall into three categories: those projects associated with the development, adoption, and implementation of watershed strategies.

In the SAV and PAR projects category, there are three key elements. These are SAV mapping, water quality, PAR monitoring, and the modeling of PAR.

SAV mapping is needed to show what progress is being made in our efforts to preserve and protect the SAV resource. Under this schedule, SAV mapping projects are scheduled to occur every two years at an estimated cost of $40,000 per project.

Bathymetry is an adjunct to the mapping project which will help us in determining our progress in meeting the goal of SAV growing to a depth of two meters. Given the gentle slope of the lagoon bottom where a difference in depth of a several centimeters may result in large differences in area, a fine scale bathymetry project may be required. A lagoon-wide bathymetric mapping project is scheduled for the second year at an estimated cost of $50,000.

Water quality and PAR monitoring are another critical element of this effort. The present water quality and PAR monitoring network described by John Higman will, in all probability, need to be modified and supplemented.

A segmentation scheme for further analysis and modeling, based on SAV and bathymetric maps PAR and water quality data, pollutants loading information, hydronamics, and other pertinent information will need to be developed. Additional monitoring and development of a segmentation scheme will also include additional costs, possibly by an additional $100,000 per year to $300,000 lagoon-wide.

The final element in this category is water quality and PAR modeling scheduled to occur in the third and fourth year of the projects. Through the use of water quality and PAR data, each segment will be analyzed, the primary factor affecting light penetration identified, and recommendations made for water quality standards. Our estimate for this project is $50,000.

The watershed management strategies portion of the project is fairly straight forward. In the initial phase, several demonstration projects targeted at controlling one or more of the primary factors affecting light penetration will be funded and evaluated. Although this is an initial phase, it is anticipated that the evaluation of strategies on technologies will be recommended to be adopted and implemented on the various segments and ultimately monitored for effectiveness. Looking at the schedule, we hope to be in the implementation and monitoring stage by late 1995-early 1996. Again the realities of budgets, personnel, and bureaucracy will no doubt affect this timetable.

You will note that on the task outline sheet, each of these projects has a responsible agency or agencies, possible participants, and possible funding sources. Certainly some of these agencies will definitely be involved, others should be involved, and still others could be very helpful if they were involved. We would appreciate your thoughts on this list.

Obviously, a major consideration in this effort is funding. Given the present financial constraints on all levels of government, this is a prime consideration. It is anticipated that IRLNEP, SWIM and the water management districts and others will continue to fund certain activities that they are now undertaking that will become part of the SAV project. Other portions of the project, however, may require seeking assistance from some of these other agencies, some of which are listed here.

Where do we go from here? If this approach and the general schedule are appropriate, the immediate issue is the modification and enhancement of the existing lagoon monitoring network to develop adequate data for the modeling effort. IRLNEP presently had funds available shortly through the upcoming (1992) workplan to assist in this process. We have a good monitoring network in place, but the system needs some fine tuning and enhancement to meet the needs of this project.

In closing, we realize this schedule is ambitious. However, we look forward to your assistance in making this project happen.

DISCUSSION OF ISSUES, GOALS, OBJECTIVES

Submerged Aquatic Vegetation (SAV) is a critical component of the Indian River Lagoon ecosystem. Since the 1950's, however, the aerial extent of SAV within the lagoon has been dramatically reduced. Estimated losses of SAV have reached 100% in certain areas of the lagoon (DNR,1985).

This decline in SAV coverage has been largely attributed to adverse water quality conditions, particularly the reduction in water clarity. The reduction in water clarity has resulted in reduced light penetration through the water column with a reduction in light availability to SAV. This reduction in turn affects the viability of the SAV community.

This workshop allowed local scientists, planners and project staff to address the SAV Initiative. The Initiative was conceived with the goal of developing a standard to measure water quality on a watershed basis.

DISCUSSION OF STRATEGIES AND PROJECTS

During the second day of the workshop, participating scientists shared their impressions and knowledge for accomplishing the five tasks set forth by the Initiative to attain the program's goal of restoring and maintaining the Indian River Lagoon. These tasks include:

a. Inventory of SAV throughout the Indian River Lagoon system
b. Analysis of factors causing loss of SAV
c. Recommendations for controlling factors causing SAV decline
d. Recommendations for strategies and methodologies to maintain existing SAV habitat and restoration or rehabilitation of SAV in impacted areas.
e. Recommendations for continued assessment of SAV

1. Inventory of SAV Throughout the Indian River Lagoon System

The group agreed that mapping will be completed by the St. Johns River Water Management District as recommended in SAVI. The mapping is scheduled for completion in January 1993.

2. Analysis of Factors Causing Loss of SAV

Implementing a monitoring network will allow for the analysis of factors causing seagrass loss. Participants agreed that the existing IRL Water Quality Monitoring Network offers some information for analysis. However, the group conceded that the network was in need of expansion, most specifically a network which studies the PAR, color, TSS, DIN, and chlorophyll.

3. Recommendations for Controlling Factors Causing SAV Decline

This particular task will be addressed by parameters set forth in the SAV Initiative, including availability of light, epiphyte abundance, and patterns of turbidity in the lagoon based on either circulation and flushing.

4. Recommendations for Strategies and Methodologies to Maintain Existing SAV Habitat and Restoration or Rehabilitation of SAV in Impacted Areas

Participants agreed that a standard is needed, either numeric or narrative, measuring the loss of productive, functional seagrass beds in the lagoon. Such a standard could be adopted by law. Many standards require permitting and often only add to the red tape in a regulatory system. Workshop participants agreed to develop a narrative standard.

5. Recommendations for Continued Assessment of SAV

Participants agreed with the continued assessment of SAV in the lagoon, and recommended annual mapping and the adoption of a standard to permit this assessment. In addition, participants questioned why functionality was not included in the SAV Initiative. The group agreed that the scope of the Initiative needed to be limited to focus on restoring seagrasses as a habitat, not necessarily restoring the vitality of the entire system.

Participants agreed that the workshop addresses the restoration of seagrass as a habitat. Components such as algae, sediments, mangroves, and others were not necessarily discussed, but were noted as beyond the scope of the Initiative and may require additional funding in the future.

INSTITUTIONAL REALITIES OF SAVI

by

Louis C. Burney
Florida Department of Environmental Protection
3900 Commonwealth Blvd.
Tallahassee, FL 32399-3000

Mr. Burney is an Environmental Specialist with the Florida Department of Environmental Protection (DEP), with 22 years experience in coastal resource management. He received his B.S. and M.S. in Geography from Florida State University where he concentrated his studies in Land Use Planning and Natural Resources Management. Upon graduation from F.S.U. in 1970, Mr. Burney became the first land use planner employed by the Florida Board of Trustees of the Internal Improvement Trust Fund (State Lands Management). For the past 20 years he has been working with the state's Coastal Zone Management Program, where he has led numerous initiatives toward improving Florida's statewide capabilities for protecting and managing our threatened coastal resources. He spearheaded the establishment of the Rookery Bay and Apalachicola Bay estuaries as National Estuarine Research Reserves, and was instrumental in the establishment of the Florida Keys as an "Area of Critical State Concern". In 1990, Mr. Burney authored legislation calling for elimination of domestic wastewater discharges to Indian River Lagoon by 1995. His current responsibilities at DEP include helping to develop and coordinate a joint DEP/Water Management District "Water Resources Planning Initiative", which seeks to improve the statewide consistency and effectiveness of DEP and WMD water resource management programs.

INTRODUCTION

Technical workshops stand the risk of becoming so deeply involved in specific issues that the broader management objectives may become blurred. Because of this, it is appropriate to occasionally take stock of events and try to put matters in proper perspective. I was asked to provide my thoughts on the general directions and strategy being discussed for the SAV Initiative, and to help put the topic in perspective with the realities of existing management programs. In order to do this, it may be helpful to first recount some of my impressions from the November, 1990 Seagrass Workshop in West Palm Beach.

Based on my meeting notes, I believe a general consensus was developed on several fundamental points. Among these were the following:

a) At least 10 to 20 percent of available surface light is needed to sustain healthy SAV, and in general, reduced water clarity will result in reduced seagrass viability.

b) Present monitoring is inadequate to deal with seagrass impacts, but care must be taken to assure that seagrass monitoring does not become an end unto itself. To be of value, monitoring must be closely linked to management.

c) There are technical problems with the existing Florida transparency standard, and it will not protect seagrasses. Major concerns are:
- It assumes that the current estuarine environment is healthy.
- It assumes that a small amount of degradation can be absorbed by the system with no measurable effect.

d) Despite the shortcomings of its transparency standard, Florida is the only state that has adopted a transparency standard.

e) We have long ago exceeded the buffering capacity of Indian River Lagoon to absorb human insults, and based on existing knowledge:
- New pollutant loadings to the Lagoon must be prevented, and
- Existing loadings must be reduced in the face of increasing human population.

f) There is a growing awareness that reliance on numeric water quality standards and case-by-case permitting as the primary means of protecting living estuarine resources is ineffective.

g) For Indian River Lagoon, the viability of seagrasses is probably the best single indicator of overall health of the estuary.

While a variety of valuable technical information was exchanged at the workshop, from a management perspective, the above conclusions were some of the real "meat" of the event. These are the types of "bottom lines" that strike me as being especially useful for focusing management actions toward clear objectives. They are useful because they represent a conversion of complicated technical considerations into valid generalizations that can be understood by non-scientists and, especially, politicians. In regard to directions for future research, it was noted at the workshop that one of the most serious handicaps for managers was the absence of practical monitoring and interpretive frameworks capable of providing "early warning" of declines in overall health of estuarine systems. Such frameworks are sorely needed to provide a basis for timely corrective actions before damage to the system becomes critical. They are also needed to assess the effectiveness of major management actions.

With that as background, let me offer a few of my perceptions about agency programs and the SAV initiative being considered. In trying to deal with estuarine management issues, it has been my observation that regulatory programs are often handicapped by an inability to develop practical applications for generally-accepted scientific principles. This is partially because of a prevailing "mindset" that tends to confuse regulation and case-by-case permitting with "management". However, this mentality is rapidly changing. Looking into the future, I believe that in Florida you will see a greater emphasis on more comprehensive, waterbody or ecosystem-wide management approaches that are tailored to waterbody-specific needs. These approaches will more clearly reflect a management view that regulations and permitting programs are basically tools that help implement, rather than drive long-term strategies and policy. These approaches will also reflect a greater reliance on application of generally-accepted scientific principles and informed judgement, rather than waiting for scientific "proof". Experiences gained in one waterbody will more frequently serve as a basis for management actions in other waterbodies. There will be a greater reliance on multiple indicators of estuarine health, as opposed to relying primarily on water quality standards. There also will be greater use of waterbody-specific policy to guide management programs, and more active involvement by local governments.

To put these thoughts in perspective, it might be helpful to review recent events involving domestic wastewater discharges into Indian River Lagoon as a case example. I seriously doubt that anyone having a basic understanding of estuarine dynamics would condone the present practice of discharging domestic wastewater into Indian River Lagoon. However, permitting of the existing discharges is a classic example of how government makes decisions which try to balance competing public interests, often with incomplete information or inaccurate assumptions. Quite simply, the discharges were permitted during a period when it was generally accepted by both state and federal water quality permitting programs that estuaries could assimilate such discharges with negligible effects. As these programs acquired better scientific understandings, there was a gradual shift in regulatory attitude, and incremental actions were taken to eliminate domestic wastewater discharges from the lagoon wherever possible.

Over a decade or so, state regulators were persuasive in getting at least half of the former number of discharges eliminated. They were also successful in getting higher levels of treatment for the remaining discharges. However, the discharges that were eliminated were the relatively "easy" ones. Those remaining presented a much greater challenge. Part of the reason for this was that the permitting system relied on case-by-case examination of each facility's potential impacts (primarily impacts on dissolved oxygen levels during worst times of the year). Also, because of the higher direct costs of other wastewater disposal options, outright denial of permit renewal applications for municipal wastewater discharges was difficult. Historically, in order to deny such permits, the state generally had to provide convincing evidence that the discharge would violate state water quality standards. Often there was only a limited capability to do this. While recent improvements have been realized in evaluation procedures, the rather narrow scope of past permit evaluations could not adequately account for aggregate impacts and often overlooked important considerations regarding the geochemistry and overall health of the estuarine system.

Taking a different, more holistic approach, the State legislation which created the statewide SWIM program called for comprehensive strategies to restore and maintain priority waterbodies as ecological systems. Accordingly, the adopted Indian River Lagoon SWIM Plan emphasized the critical need to reduce point and nonpoint source nutrient loadings to the lagoon system, and specifically recognized the need for legislation to accelerate removal of domestic wastewater discharges from the lagoon. This timely recommendation provided a basis for waterbody-specific legislation, enacted in 1990, which prohibits DEP from issuing permits for new or expanded domestic wastewater discharges into the Indian River Lagoon system, and requires removal of all such existing discharges from the lagoon by July 1, 1995.

The point I would like to make here is that the "no-discharge" policy established by this legislation was not based on detailed modeling or rigorous studies of cause-and-effect. It was based on the application of generally-accepted scientific principles regarding the effects of excessive nutrient loadings to estuaries. A key ingredient in successful passage of the law was a general consensus of scientists that the Indian River Lagoon system was showing clear signs of nutrient-related stress, and that this stress was most pronounced in the vicinity of municipal wastewater outfalls. Put in this broader, system-wide perspective, the simple logic and unmistakable management implications were that unless these particular nutrient loadings to the lagoon were eliminated, the restoration goals of the SWIM Act could not be achieved. Furthermore, the economic and social benefits of the lagoon system (which greatly outweigh the costs of eliminating the discharges) were in serious jeopardy. This was a politically powerful argument, and is the type of argument that increasingly needs to be presented in estuarine management forums. Personally, I would like to see similar discharge policies for nutrient sensitive estuaries, statewide -- not only to protect estuarine resources, but also to reduce unnecessary governmental studies and expense associated with case-by-case permitting. It has been my experience that the lack of detailed information regarding specific cause-and-effect is a "red herring" that is often presented by regulated interests to justify the status quo. In the absence of system-wide management strategies and clear protective policies, this tactic has generally been successful.

However, if strict protective policies are to survive challenges by regulated interests, there must be convincing evidence that such policies are in the overall public interest and that they are achieving their stated purposes. For the Indian River Lagoon system, monitoring the extent and viability of seagrasses would seem to be a logical step toward this end, especially in areas where point sources have been removed and areas near retrofitted stormwater systems. Also, assuming that light attenuation monitoring can be conducted in a reliable, cost-effective manner, the light attenuation/seagrass model seems promising as a diagnostic and predictive tool. But I caution you to not "oversell" the concept, and to keep your energies clearly focused on meeting recognized management needs, to the degree that this is possible. In other words, as was advised by Robin Lewis at the previous seagrass workshop, you need to "get real".

In line with this thought, I must admit that I am a little apprehensive that the light attenuation/seagrass model, as I understand it, may be somewhat limited in its value for direct application in regulatory programs. On the positive side, by linking the light requirements of seagrasses to the light attenuating properties of water, the model can potentially define the theoretical depth and spatial limits of seagrass survival. In this sense, the concept appears capable of providing the "bottom line" type of conclusions that I think are needed by managers. However, as each of you are well aware, the dynamics of estuaries are complex. Considering the many uncertainties involved, and the fact that seagrasses have vanished from shallow areas of the lagoon which apparently have ample light penetration, it seems to me that factors other than light attenuation may be limiting seagrass survival in at least some cases. This consideration must be taken into account in any future management applications of the concept.

Additionally, in line with the "get real" advice, I feel I must address the topic of developing a better numeric transparency standard for regulatory purposes. In order to be used effectively as a standard in permitting, the potential light attenuation effects from a regulated activity (e.g., a specific nutrient discharge) should be predictable, or at least be "estimable". I do not believe the capability presently exists to do this reliably and cost-effectively. Also, as mentioned earlier, numerical water column standards may not be the most effective way of protecting living estuarine resources. Under these circumstances, to pursue adoption of a new transparency standard would, in my opinion, be an exercise in futility. It would misdirect energies toward administrative processes that ultimately will not meet your expectations for restoring and protecting seagrasses in Indian River Lagoon. Also, use of the term "standard" in reference to target transparency conditions should be avoided when dealing with the existing water quality management programs. A final point I will make is that water transparency targets seem very useful for assessing potential resource recovery effects of management strategies or policy options. As such, they should be useful for developing benchmarks or reference points for assessing progress toward restoration of overall estuarine health. But I would recommend against using them to drive specific management actions in adjacent uplands.

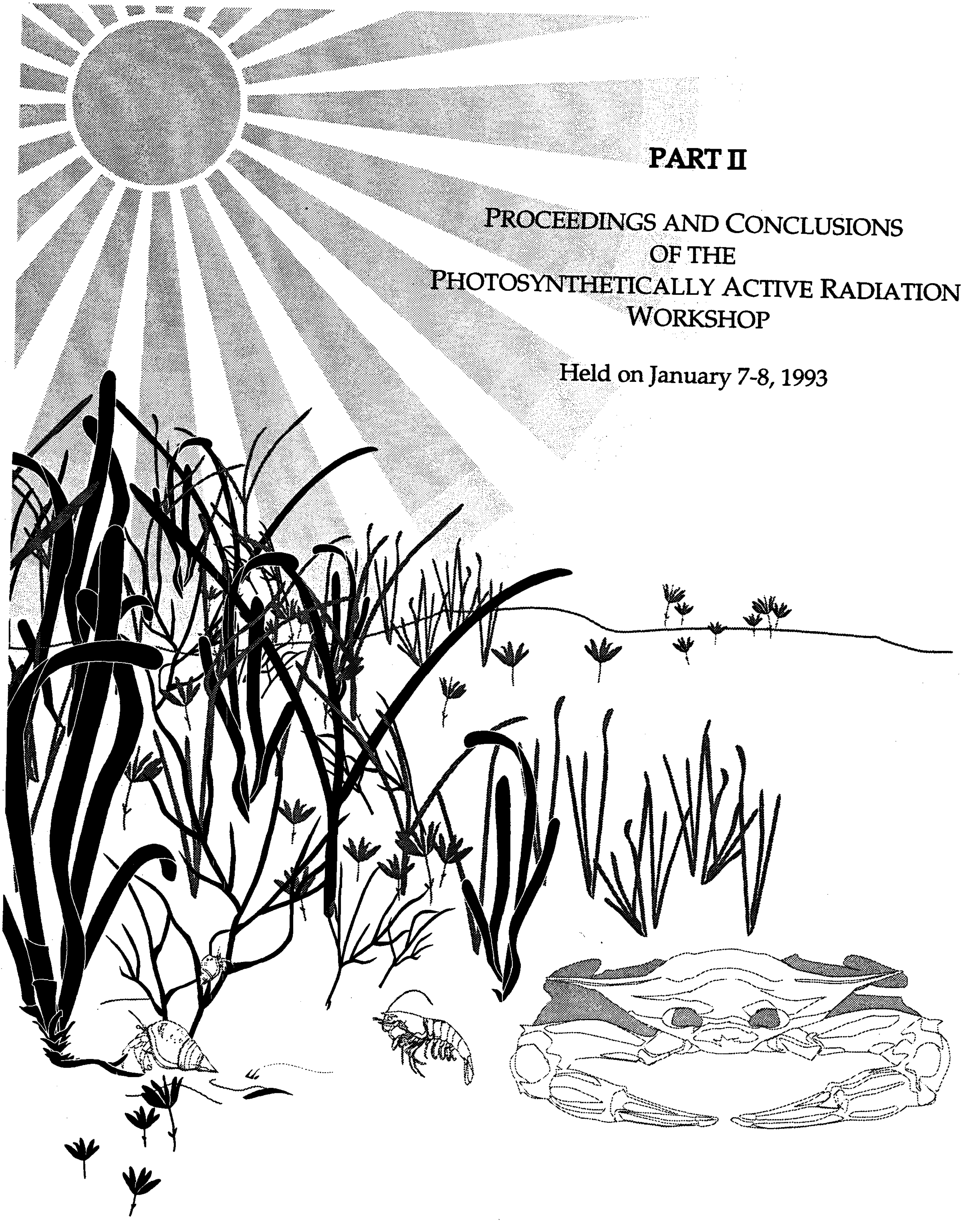
I must stress that my comments are not intended to dampen further scientific inquiry into light attenuation/seagrass relationships. Rather, I am suggesting that, to be effective, we must be able to apply the understandings within Florida's existing institutional and management framework. Several federal, state, and water management district programs are already moving in the direction of comprehensive watershed management, with a central focus on reducing overall loadings of nutrients and other contaminants. Legally enforceable deadlines have been established for eliminating the primary point source nutrient loadings from Indian River Lagoon. The existing Indian River Lagoon SWIM Plan is being revised to include interim stormwater pollutant load reduction goals and a schedule for establishing "final" pollutant load reduction goals. The St. Johns River and South Florida Water Management Districts are developing comprehensive water resource management plans for their respective regions of the state, as are the other Water Management Districts. And, as you know, the National Estuary Program (NEP) is trying to establish the long-term commitments needed to assure continuity of effort over time. If the actions already prescribed in these and other existing programs are fulfilled, it would be reasonable to expect at least some improvement in the overall health of Indian River Lagoon.

In conclusion, I would urge you to try to find ways to provide technical support for these ongoing management programs. In particular, efforts toward refining and developing practical applications for the light attenuation/seagrass model should be a priority research topic. Seagrass monitoring should proceed along the lines already discussed. Other interpretive tools which can help provide multiple indicators of trends in overall health of estuarine systems are also needed. The sooner they can be developed and applied, the better. Hopefully, NEP can develop the strategies and commitments needed to help make these good things happen.

PART II

PROCEEDINGS AND CONCLUSIONS OF THE PHOTOSYNTHETICALLY ACTIVE RADIATION WORKSHOP

Held on January 7-8, 1993



PAR SECTION 1:

INTRODUCTION

PAR/SAV Monitoring Workshop
An Introduction

by

Lori J. Morris
St. Johns River Water Management District
P.O. Box 1429
Palatka, FL 32178

Light availability is one of the major factors determining growth and survivorship of seagrasses. Factors limiting light availability include scattering and absorption of PAR by suspended particulates (turbidity and phytoplankton) and dissolved substances (Kirk, 1983).

In order for the Indian River Lagoon Surface Water Improvement and Management (SWIM) and the National Estuary Programs (NEP) to achieve their primary goal of attaining and maintaining a functioning macrophyte-based ecosystem, a well-integrated monitoring program needed to be developed. Since seagrasses have been designated as a primary habitat of concern for protection and restoration in the Indian River Lagoon, the monitoring program will include:

* Lagoon-wide seagrass mapping
* Site-specific seagrass monitoring
* Modeling the impact of water quality on water clarity and thus on seagrass.

Before any water quality targets for seagrass growth can be developed the relationship between water clarity parameters and seagrass health needs to be determined. Part of this need is met by the Water Quality/Photosynthetically Active Radiation (WQ/PAR) Monitoring Network.

The WQ/PAR Monitoring Network was established by the St. Johns River Water Management District (SJRWMD) in 1988. This network is composed of seven agencies, from five counties covering over 250 km in the Indian River Lagoon.

Each agency measures water quality parameters and PAR at least monthly, some weekly and some bi-weekly. The main goal of the Network is to:

* Identify problem areas
* Complement other studies developing the SAV/WQ relationship
* Guide future water quality monitoring efforts by maximizing information collected while minimizing costs
* Develop WQ targets as the basis for PLRGS (pollution load reduction goals)

In order to compare the different areas of the Lagoon, a reliable and standardized method of data collection needs to be adopted by all agencies. Water quality sampling has been strictly regulated by the Department of Environmental Protection's (DEP) Quality Assurance/Quality Control (QA/QC) Plan. However, there has never been a standard method for measuring light attenuation in the water column. Each agency was using different equipment and protocols to measure attenuation. These discrepancies caused problems in analyzing the light data and comparing results. Therefore, the main goal for this workshop was to develop a reliable standard method for measuring light attenuation in the water column. This method includes appropriate sensors to use, exact protocol to follow, and when to measure PAR.

The following proceedings summarize the current research and the consensus on most appropriate protocol for measuring light in the submerged environment relevant to SAV. The new protocol for measuring PAR in the Lagoon is being adopted into the WQ/PAR Monitoring Network.

LITERATURE CITED

Kirk, J.T.O. 1983. Light and Photosynthesis in Aquatic Ecosystems. Cambridge University Press, Cambridge.

PAR SECTION 2:

PAR/SAV RELATIONSHIPS

THEORETICAL CONSIDERATIONS IN THE USE OF 2PI OR 4PI SENSORS TO MEASURE UNDERWATER LIGHT PENETRATION FOR MONITORING SEAGRASS HABITATS

by

Charles L. Gallegos, Ph.D.
Smithsonian Environmental Research Center
P. O. Box 28
Edgewater, MD 21037

This paper discusses differences between 2pi and 4pi sensors as they relate to the measurement of underwater light fields relevant to the survival of seagrasses. Emphasis is on the relationship of the theoretical quantities measured by the 2 sensor types to the equations of radiative transport, rather than operational characteristics of the sensors themselves.

It is useful to begin by explaining some defined quantities of interest (Figure 1; Morel and Smith 1982). The most fundamental quantity is radiance, *L*. Radiance is defined as radiant flux in a given direction per unit solid angle per unit projected area, and has units W m^{-2} sr^{-1}. Other fluxes of interest are defined in terms of radiance.

The downward or downwelling irradiance, denoted E_d, is the radiant flux per unit area on a horizontal surface, which is computed as the integral of the radiance weighted by the cosine of the zenith angle over the upper hemisphere. This is the quantity measured by a 2pi sensor. Upward or upwelling irradiance, E_u, is similarly defined for the lower hemisphere; and net downward irradiance, E_z, is the difference between the two. Scalar irradiance, E_0, the quantity measured by a 4pi sensor, is the integral of the radiance over all directions, hence the term 4pi. The integral is **not** weighted by the cosine of the zenith angle.

Another important term is the average cosine, μ, which is the ratio of the net downwelling irradiance to the scalar irradiance, i.e. E_z/E_0. An interpretation of μ is that it is the cosine of the angle at which one would have to bundle the given scalar flux in order to produce the same net downwelling flux. It is a measure of

Figure 1.

Terminology and Units in Optical Oceanography
Morel, A. and R. C. Smith. 1982. Marine Geodesy 5:335-349.

Downward Irradiance	E_d	The radiant flux on an infinitesimal element of the upper face of a horizontal surface divided by the area of the element. Alternatively, downward irradiance is the integral of the radiance, weighted by the cosine of the zenith angle (θ), over the upper hemisphere.
Upward Irradiance	E_u	The radiant flux incident on an infinitesimal element of the lower face of a horizontal surface divided by the area of the element. Alternatively, the upward irradiance is the integral of the radiance, weighted by the cosine of the nadir angle ($\pi-\theta$), over the lower hemisphere.
Downward vector Irradiance, net (downward) Irradiance	E_z $\bar{E}$	The net irradiance is given as the difference between the downward and upward irradiance, with a horizontal plane as reference.
Scalar Irradiance	E_o	The integral of radiance distribution at a point over all directions about the point.
Average Cosine	$\bar{\mu}$	The ratio of the net (downward) irradiance to scalar irradiance. Relation: $\mu = \frac{E}{E_0} = \frac{E_d - E_u}{E_0}$
Vertical attenuation coefficient of a radiometric (X) quanity (such as any of the radiance or irradiances defined above)	k	Vertical gradient of the natural logarithm of the quantity. Relation: $k = -\frac{1}{X}\frac{dX}{d_z} = -\frac{d\ln(X)}{d_z}$ (z=depth)

the diffuseness of the light field; the lower the value, the more diffuse is the light field. In the limiting case of a perfectly uniform light field, there would be as much upwelling as downwelling irradiance; to represent the scalar flux as parallel rays, they would have to be traveling horizontally, which is an angle of pi/2 to the zenith and has a cosine of 0.

Finally, note that, according to Morel and Smith (1982), vertical attenuation coefficients can be defined for any radiometric quantity given above, as well as for some others not given here. k is defined as the instantaneous fractional derivative with respect to depth of the quantity of interest. The negative sign is due to the choice of depth positive in the downward direction. Operationally the attenuation coefficient is computed as the derivative of the logarithm of the quantity. Because the attenuation coefficients are defined entities, we cannot say that one or the other does not exist theoretically.

Which sensor is most appropriate for monitoring light availability for seagrasses? The answer depends more on the biology of factors determining the lower limit of seagrass beds than on the optical properties of the sensors. If the important quantity is the photon flux available to solitary shoots as the canopy begins to thin out (*see* Figure 2), then it is easy to argue that the directionality of the photons is irrelavant; photons traveling in all directions are equally capable of being absorbed and driving photosynthesis. This flux is best measured by a 4pi sensor.

Alternatively, if the limiting factor is the photon flux incident on a (hypothetically) flat surface determining the light availability to emerging shoots (*see* Figure 3), then upwelling flux is unavailable, and obliquely traveling photons are spread out over a larger area. In that case, downwelling irradiance as measured by a 2pi sensor would be the appropriate measure of light availability.

Both scalar and downwelling irradiance are, however, instantaneous photon flux densities. As such, they are subject to diurnal fluctuations and can change rapidly due to cloud cover, and thus are not useful for characterizing light fields for seagrasses in a water quality monitoring program. Generally, the criterion for seagrass survival is given as a long-term average of the percentage of surface irradiance reaching a depth. This percentage is best expressed in terms of the attenuation coefficient, so it is instructive to see how the diffuse attenuation coefficients for downwelling and scalar irradiance relate to one another and to the equations of radiative transport.

Figure 2. Hypothetical schematic diagram of depth-limitation of seagrass beds by irradiance available to mature, solitary blades. This flux is best described by photon scalar irradiance and is measured by a spherical sensor.

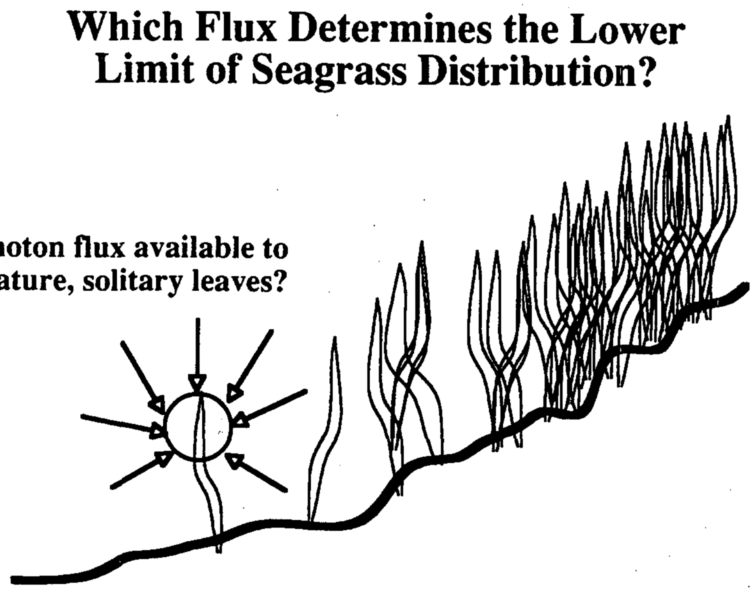


Figure 3. Hypothetical schematic diagram of depth-limitation of seagrass beds by irradiance reaching propagules emerging from the bottom. This flux is best described by downwelling irradiance and is measured by a cosine-corrected sensor.

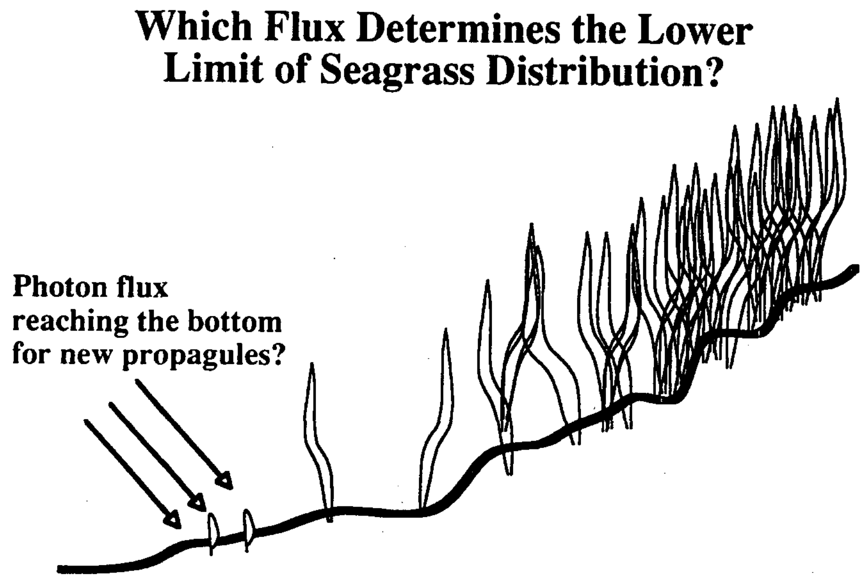


Figure 4. Diagram of the sources and sinks of photons in a small, incremental solid angle. Photons traveling in a given direction may be lost due to absorption (by particles, dissolved matter, or water), or by being scattered (primarily by particles) into another direction. Photons in a small solid angle are gained by scattering of photons previously traveling in other directions. Integration of the equation over the entire sphere yields Gershun's law. See Jerlov (1968) for further details.

Radiative Transfer Equation

$$\frac{dL(z,\theta,\phi)}{dz}\cos\theta = -cL(z,\theta,\phi) + L^*(z,\theta,\phi)$$

Scattering Source

$$L^*(z,\theta,\phi) = \int_{\Phi'=0}^{2\pi}\int_{\theta'=0}^{\pi}\beta(\theta,\phi;\theta',\phi')L(z,\theta',\phi')\sin\theta' d\theta' d\phi'$$

Gershun's Law

$$\frac{d(E_d - E_u)}{dz} = -cE_0 + bE_0 = -aE_0$$

Transmittance

$$c = \frac{L^*}{L} - \frac{1}{L}\cdot\frac{dL}{dr}$$

$$c = -\frac{1}{L}\cdot\frac{dL}{dr}$$

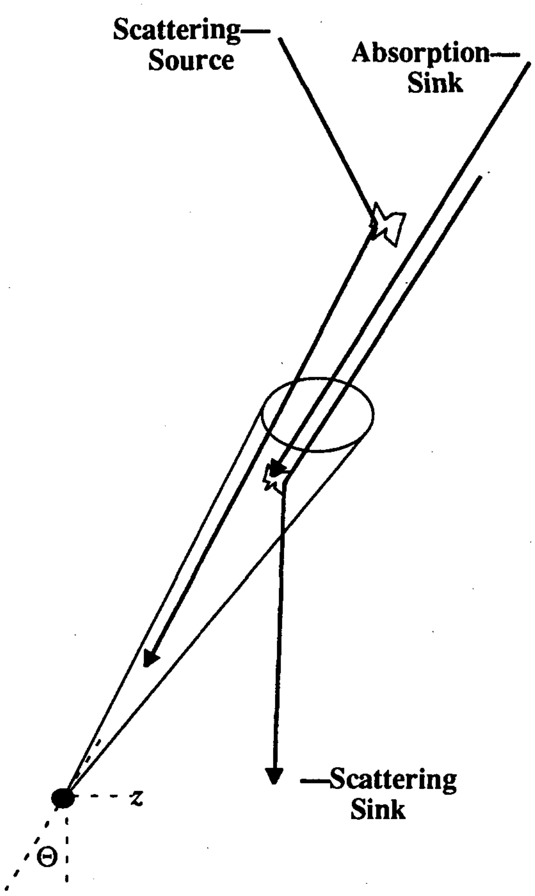


Figure 5. Derivation of diffuse attenuation coefficient for photon scalar irradiance from Gershun's law and definition of average cosine, μ.

Scalar Irradiance

Gershun's Law

$$\frac{d(E_d - E_u)}{dz} = -cE_0 + bE_0 = -aE_0$$

Recall Definition of mean cosine, μ

$$\mu = \frac{(E_d - E_u)}{E_0} \Rightarrow (E_d - E_u) = \mu E_0$$

Substitute into Gershun's Law and expand:

$$\frac{d(\mu E_0)}{dz} = -aE_0$$

$$\mu \frac{dE_0}{dz} + E_0 \frac{d\mu}{dz} = -aE_0$$

Divide through by μE_0 and rearrange:

$$\frac{1}{E_0}\frac{dE_0}{dz} + \frac{1}{\mu}\frac{d\mu}{dz} = -\frac{a}{\mu}$$

$$k_0 \equiv -\frac{1}{E_0}\frac{dE_0}{dz} = \frac{a}{\mu} + \frac{1}{\mu}\frac{d\mu}{dz}$$

Figure 6. Derivation of diffuse attenuation coefficient for downward irradiance from Gershun's law and definition of irradiance ratio (i.e. reflectance), *r*.

Downwelling, Cosine Irradiance

Gershun's Law

$$\frac{d(E_d - E_u)}{dz} = -cE_0 + bE_0 = -aE_0$$

Define Irradiance Ratio (Reflectance), r

$$r \equiv \frac{E_u}{E_d} \Rightarrow E_u = rE_d$$

Substitute into Gershun's Law

$$\frac{d[E_d(1-r)]}{dz} = -a\frac{E_d(1-r)}{\mu}$$

$$(1-r)\frac{dE_d}{dz} - E_d\frac{dr}{dz} = -a\frac{E_d(1-r)}{\mu}$$

Divide through by $E_d(1-r)$ and rearrange,

$$k_d \equiv -\frac{1}{E_d}\frac{dE_d}{dz} = \frac{a}{\mu} - \frac{1}{1-r}\frac{dr}{dz}$$

The equation of radiative transport is written in terms of radiance, L (Figure 4). It states that radiance is removed from a small solid angle increment due to absorption which extinguishes photons, and due to scattering, which redirects photons out of the solid angle (Figure 4, *Scattering Sink*). Radiance is added to an incremental solid angle by scattering from all other directions (Figure 4, *Scattering Source*). It is the complexity of this scattering term that causes most investigators to resort to Monte Carlo methods to study the behavior of the equation.

The Lambert-Beer law with a constant attenuation coefficient either for scalar or for downwelling irradiance **does not** constitute a solution of the radiative transport equation. However, integration of the equation over the entire sphere yields a useful expression, known as Gershun's Law, which states that absorption in a depth stratum is proportional to scalar irradiance, and is the only process that attenuates the **net** downwelling flux (Figure 4).

Using Gershun's Law in conjunction with the definitions for the attenuation coefficients given previously (Figure 1) we can see how attenuation coefficients for 2pi and 4pi sensors depend on changes in the radiance distribution and how they relate to one another. For scalar irradiance (Figure 5), we start with Gershun's Law and recall the definition of the average cosine, μ. Substituting for net downwelling irradiance and expanding the derivative, we find that the scalar diffuse attenuation is given by the sum of a/μ, and a term that depends on the change in the radiance distribution with depth (Figure 5).

Similarly for downwelling irradiance (Figure 6), we begin with Gershun's Law, and define the irradiance ratio or reflectance, r, as the ratio of the upwelling to the downwelling irradiance. Substituting and expanding as before, we find that the attenuation coefficient for downwelling irradiance also depends on a/μ minus a term that depends on the change of reflectance with depth (Figure 6).

To see how these coefficients might compare with one another, it is necessary to examine the depth profiles of average cosine and reflectance computed by Monte Carlo simulation of the complete equations of radiative transport (Figure 1 *in* Kirk 1981). There is an asymptotic radiance distribution at great optical depth below which the depth derivatives of μ and r vanish (Jerlov, 1968). In this region the 4pi and 2pi attenuation coefficients are identical. For seagrasses, however, we are interested in the shallower optical depths where the radiance distribution is changing. Figures 5 and 6 show that each coefficient begins as the ratio of a/μ. Examination of Figure 1 in Kirk (1981) shows that, for 4pi measurements, μ starts out higher than its asymptote and decreases; thus for scalar irradiance, a term with a negative sign is added to a/μ in the near-surface region. For the 2pi attenuation coefficient, Figure 1 in Kirk (1981) shows that r begins below its asymptotic value and increases asymptotically with depth; thus we subtract a term with a positive sign to a/μ to get k_d. To a first approximation the magnitude of each coefficient is set by the term a/μ, and to a second approximation, they change in the same direction. At great optical depth the coefficients are necessarily identical. Thus, we should expect that the attenuation coefficients should not differ greatly from one another.

As a test, I examined data taken with a co-planar array of Licor sensors in some turbid farm ponds and in an experimental tank (Figure 7). Over a wide range of

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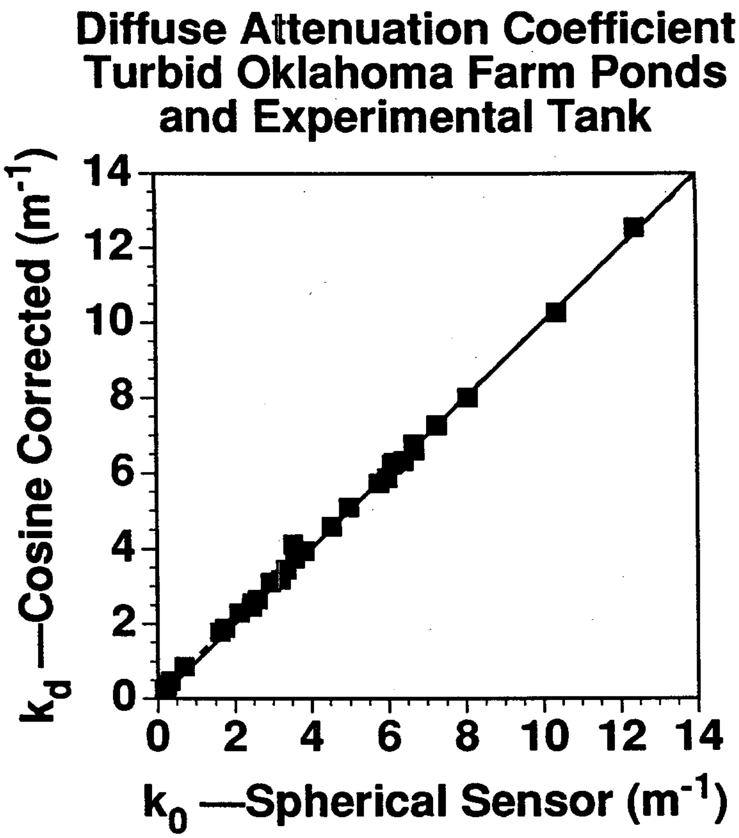
Figure 7. Data taken in an experimental tank which started with tap water and followed the course of an induced algal bloom. There was a slight tendency for higher attenuation coefficients with the 2pi sensor.



attenuation coefficients (Figure 7), 2pi and 4pi sensors gave nearly identical results, where the dashed line is the regression line and the solid line denotes 1:1 correspondence. In an experimental tank initially filled with tap water and fertilized to induce an algal bloom, there was a slight offset in the attenuation coefficients calculated by the 2 sensor types, with higher values for the 2pi sensor, but the correlation was very high and the slope was nearly one. Thus, as expected from theory, 2pi and 4pi sensors appeared to measure very similar attenuation coefficients in these systems.

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DAILY VARIABILITY IN THE MEASUREMENT OF LIGHT ATTENUATION USING SCALAR (SPHERICAL) AND DOWNWELLING QUANTUM SENSORS.[1]

by

Kenneth A. Moore
and
Jill L. Goodman
School of Marine Science
Virginia Institute of Marine Science, College of William and Mary
Gloucester Point, VA 23062

INTRODUCTION

Measurements of the underwater light environment in shallow, coastal systems have taken on increased importance as managers address the causes and effects of loss of indigenous seagrass populations (Kenworthy and Haunert, 1991; Batuik *et al.*, 1992; Dennison *et al.*, 1993). In many cases, responses of seagrass systems to environmental perturbations are studied through the use of simulation models, where seagrass survival is predicted using relationships between light availability and plant photosynthetic potential (Short, 1980; Verhagen and Nienhuis, 1983; Wetzel and Neckles, 1986). Often, empirical measures of light availability, and concurrent seagrass response (Backman and Barilotti, 1976; Dennison, 1987) are used to develop these relationships. Usually, regular but intermittent measures of light attenuation, using either submersible light meters, or secchi disks are used with more continuous measures of downwelling, atmospheric irradiance to develop models of the submarine light climate (Dennison and Alberte, 1985; Wetzel and Neckles, 1986; Zimmerman *et al.*, 1991). Therefore, it is important that estimates of light attenuation provide accurate measures of water column turbidity levels. Shallow water areas potentially can have quite variable suspended particulate loads (Ward *et al.*, 1984), and therefore short-term, or point

[1] Contribution No. 1819 from the School of Marine Science, Virginia Institute of Marine Science, College of William and Mary.

measures of light attenuation may not accurately reflect longer term turbidity levels. When these short-term measures are used with insolation records to estimate the underwater light climate, and subsequently with physiological measures of plant response to predict survival, the conclusions drawn may not be accurate.

Currently, instrumentation exists that permits continuous measurement of underwater photon flux. Only deterioration of sensor response through fouling, or other changes in calibration, limit deployment intervals. Additionally, placement of a vertical array of several sensors allows for continuous measurement of light attenuation at any one location. Finally, attenuation of submarine light with depth may be monitored by use of either scalar (spherical) or cosine-corrected (downwelling) sensors. Thus, accurate short-term measures of the underwater light environment can be obtained that provide insight into light field variability. Such measurements are useful, not only for providing empirical data for system model calibration, but also for developing sampling strategies for times, or at locations where continuous sampling of the underwater light environment is not possible.

This study reviews some continuous data gathered by the authors of underwater light-fields of photosynthetically active radiation (PAR) at several locations world-wide. Of particular interest here is simply the documentation and comparison of short-term variability of attenuation measurements in shallow-water systems, and their significance for longer term monitoring and system modeling studies, particularly of seagrass dominated regions.

METHODS

Measurements of downwelling PAR in vegetated, shallow water (<1.5m) were made using vertical arrays of two sensors placed at different depths. Scalar (4π) or cosine-corrected (2π) underwater quantum sensors (LI-Cor, Inc., models LI-193 SA and LI-192 SA, respectively) were used in the arrays. Distance between sensors was fixed at 0.25m or 0.50m, with the bottom sensors placed approximately 0.25m above the bottom. Sensors were cleaned daily each morning to minimize fouling. Data from three locations are presented here: Chincoteague Bay, Virginia, USA (37° 59'N, 75° 22'W); York River, Virginia, USA (37°16'N, 76° 20'W); Moreton Bay, Queensland, Australia (27° 30'S, 153° 22'E). Continuous measures of underwater irradiance were recorded at 10 or 15 minute intervals, and diffuse scalar (K_0) or downwelling (K_d) attenuation coefficients calculated as interval means of the exponential decay functions. Where,

$$K = - (\ln (E_{Z2} / E_{Z1}) / (Z1 - Z2))$$

and, E_{Z1} is the mean quantum irradiance of the upper sensor in µmoles sec^{-1} m^{-2}, E_{Z2} is the mean quantum irradiance of the lower sensor in µmoles sec^{-1} m^{-2}, Z1 is height of the upper sensor above the bottom, and Z2 is height of the lower sensor above the bottom. Solar insolation was recorded concurrently using both scalar and cosine-corrected sensors calibrated for measurement in air.

RESULTS

Mean diffuse downwelling scalar PAR attenuation over the photoperiod is presented in Figure 1A. for data obtained at Chincoteague Bay, June 1-27, 1991. Highest calculated attenuation coefficients are apparent in the morning and afternoon, with a marked depression at solar mid-day. There was no correlation of this apparent change in attenuation with either tidal or mean hourly wind data (Figure 1B) for the same period. Correspondence of decreasing attenuation with increasing sun angle was, however, high. Although suspended sediment data are not available for this sampling period, inputs of sediment through runoff into this coastal lagoon are slight, and most particle loading is due to wind re-suspension, and to a lesser extent tidal energy. Early morning and late day decreases in K_0 were associated with very low irradiance levels, and may be due to the presence of potentially more penetrating blue wavelengths.

In a manner similar to Chincoteague Bay, daily depressions in K_0 are evident for two sites in Moreton Bay, Australia (Figure 2A). As with Chincoteague Bay, the sites are located on the coastal lagoon side of a barrier island (Young and Kirkman 1975). At the frequency (6 hr^{-1}) of the data reported here, short-term variability in attenuation is evident. This would appear more related to variability in the water column at the sampling location, than to solar atmospheric conditions (Figure 2B).

Differences in water column attenuation measured with both scalar and cosine-corrected sensors over identical times, depths, and locations are presented in Figure 3A. During this October period in the York River, Virginia, 2π downwelling attenuation ranged from 1.1 to 1.3 times 4π attenuation. Differences

Figure 1.

A. Mean (s.e.) 30 minute, diffuse scalar PAR attenuation in Chincoteague Bay, Va., *Zostera marina* bed, June 1-30, 1991.

B. Mean (s.e.) 30 minute wind speed at Chincoteague Bay, Va., June 1-30, 1991.

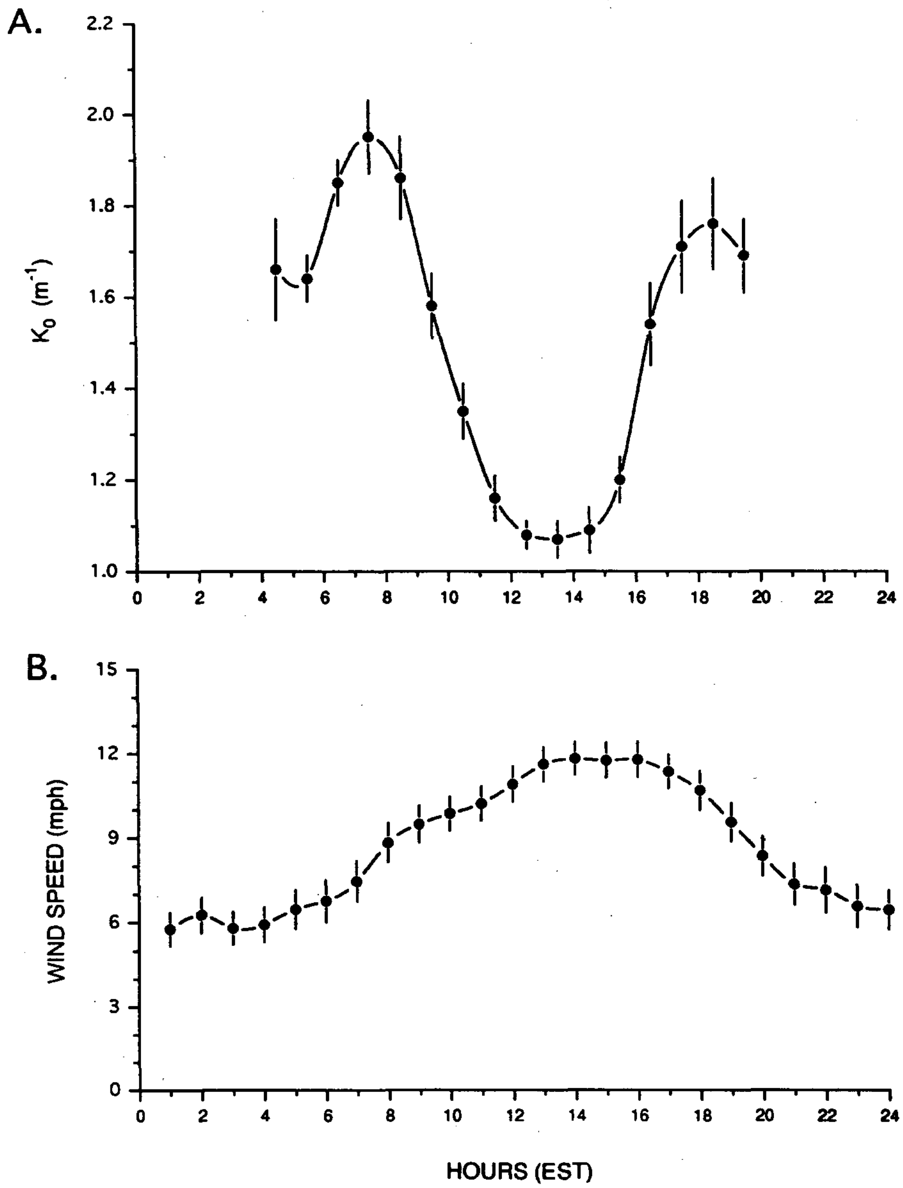


Figure. 2

A. Mean 10 minute, diffuse scalar PAR attenuation in Moreton Bay, Queensland, Dunwich and Wanga Wallen sites, January 23-29, 1993.

B. Mean 10 minute, atmospheric scalar PAR in Moreton Bay, Queensland, January 23-29, 1993.

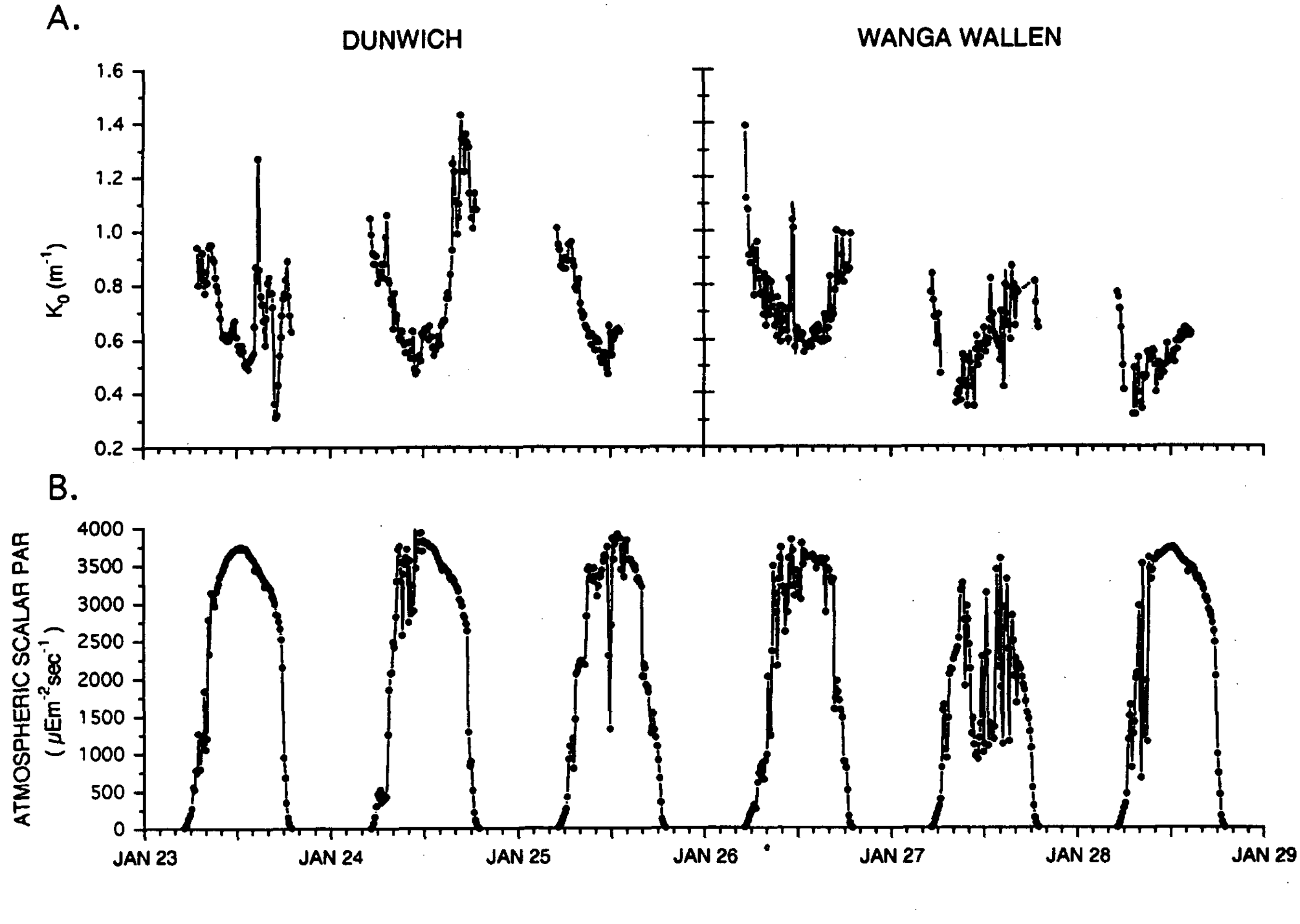
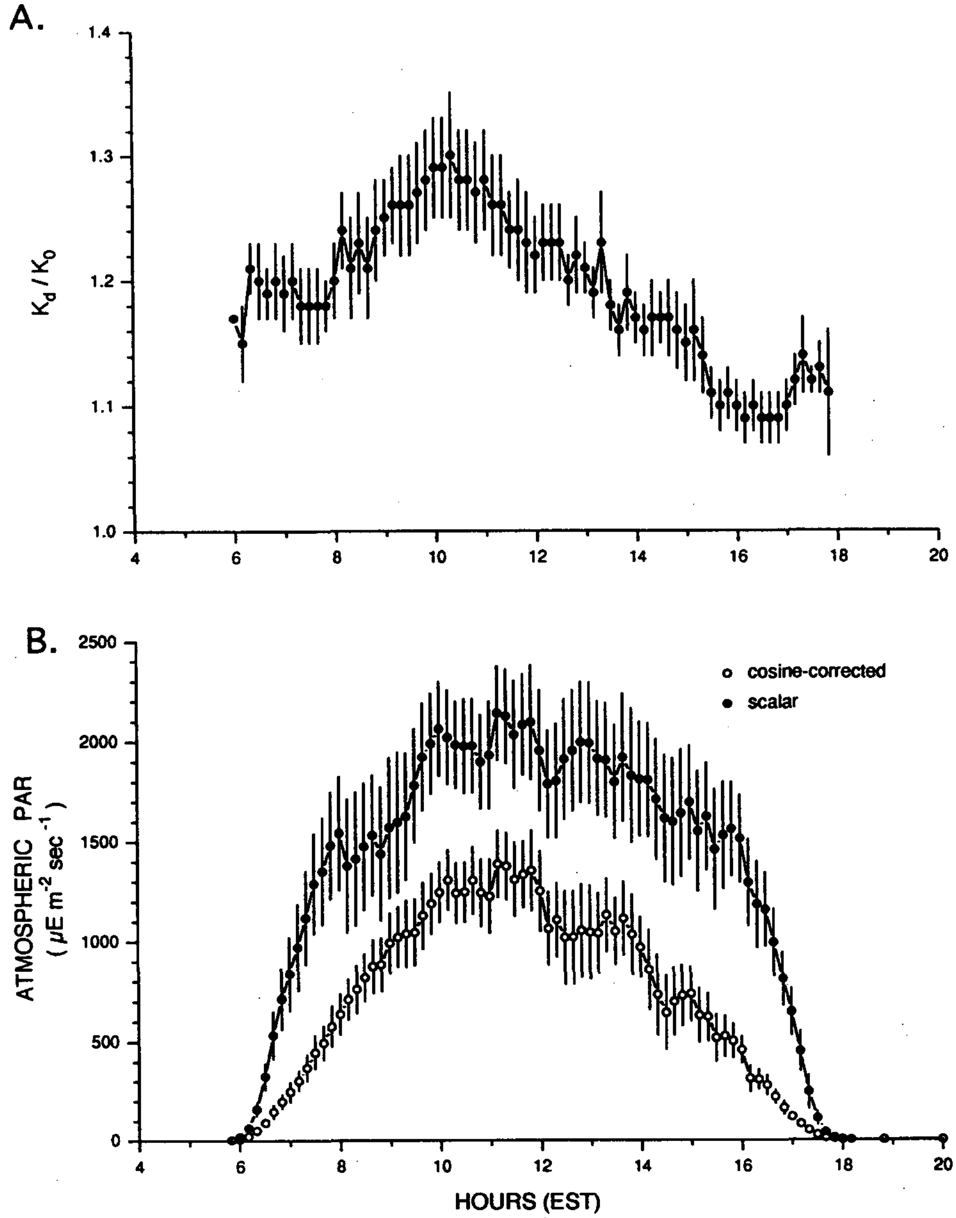


Figure. 3

A. Mean (s.e.) 10 minute, downwelling : scalar PAR attenuation ($K_d : K_0$) in the York River, Va., October 4-20, 1992.

B. Mean (s.e.) 10 minute, atmospheric scalar and downwelling PAR at the York River, Va., October 4-20, 1992.



were greatest in mid-day, and least at low sun angles in the morning and the afternoon. Differences in the response characteristics of the two sensor types are evident in Figure 3B. Not only is the light field measured by the spherical sensor greater than the downwelling sensor, but there is increased responsiveness of the scalar sensor to changes in irradiance at low sun angles in the morning and afternoon. Similar sensitivities, although not reported here, are found for both sensor types when used to measured the underwater light fields.

DISCUSSION

The results presented here suggest that the ability to predict long term submerged levels of irradiance in turbid, shallow water areas, from short term measurements of light attenuation can be influenced by a number of factors including: variability in local patterns of water column attenuation, solar altitude (and therefore time of day and time of year), and type of sensor used to measure attenuation. Robust data sets of discreet measurements made over long time periods, or in situ arrays measuring attenuation continuously for significant periods of time are necessary for accurate delineation of the variable light climate in shallow, littoral areas. Comparisons of light attenuation or light availability from different areas require that similar instruments be used or that relationships between the different measures of the light fields be developed and applied to reduce sensor effects.

In contrast to the predictions of Kirk (1983) who, using Monte Carlo calculations, estimated that K_d/K_0 should vary only between 1.01 and 1.06, our field comparisons demonstrated considerably greater variability among these two measures of light attenuation. Attenuation in the total light field that is likely used by macrophytes for photosynthesis is, therefore, underestimated by K_d. This suggest that upwelling light is an important component that needs to be considered and measured in the shallow, moderately turbid areas. Given the abundance of mineral suspended solids, their importance in optical scattering in turbid systems (Gallegos *et al.*, 1990), and their temporal and spatial variability, direct measurements of K_0 would appear necessary to adequately predict light available to the macrophytes.

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MODELING DAILY CARBON GAIN OF AQUATIC MACROPHYTES FROM QUANTUM FLUX MEASUREMENTS: A COMPARATIVE ANALYSIS

by

Richard C. Zimmerman, Ph.D. *
Department of Biology, University of California-Los Angeles,
Los Angeles, CA 90024

Alejandro Cabello-Pasini, Ph.D.
Marine Sciences Research Center, State University of New York,
Stony Brook, NY 11794

and

Randall S. Alberte, Ph.D.
Office of Naval Research
Molecular, Cell and Environmental
Biology Program, Arlington VA 22217
and
Department of Biology, University of California-Los Angeles,
Los Angeles, CA 90024

Key Words: light requirements, photosynthesis, primary productivity, carbon budget, seagrasses, submerged aquatic vegetation, H_{sat}

* Address for reprints:

Hopkins Marine Station
Pacific Grove, CA 93950
408-655-6241
408-375-2614(fax)

ABSTRACT

Time-series monitoring of light availability is commonly employed for management and protection of submerged aquatic vegetation (SAV). Sampling time scales of most programs, however, may be insufficient to resolve the temporal variation in light availability necessary for accurate evaluation of carbon gain/loss in SAV. The purpose of this study was to (1) compare the ability of different models to predict daily carbon gain in a subtidal estuarine population of *Zostera marina* L. (eelgrass) growing in Elkhorn Slough, California, (2) examine temporal variations in light availability that complicate application of these models to prediction of daily carbon gain *in situ*, and (3) suggest acceptable strategies for measuring light availability applicable to basic ecological studies as well as resource management. The non-linear nature of the instantaneous photosynthesis vs. irradiance (P vs. I) relationship, made daily integrated photosynthetic photon flux (PPF) an unreliable predictor of daily carbon gain. Numerical integration of H_{sat}, the daily period of irradiance-saturated photosynthesis, was able to predict daily carbon gain with a high degree of precision, but required the same data set as direct numerical integration of P vs. I. Models based on single daily observations of maximum noon PPF were unable to predict daily carbon gain accurately because of the high frequency variation in PPF in the estuary. Polynomial integration of P vs. I and H_{sat} models based on single daily observations of PPF showed a remarkable degree of agreement, however, indicating that they may be useful where the daily pattern of PPF is predictable. In estuaries such as Elkhorn Slough, continuous monitoring of light availability will be required for reliable management of estuarine SAV resources.

INTRODUCTION

Seagrasses form the basis of critical, yet extremely fragile ecosystems in shallow coastal embayments and estuaries throughout the world. These systems are vulnerable to anthropogenic alteration of water quality, particularly with regard to light availability (Backman and Barilotti, 1976; Dennison and Alberte, 1982, 1985, 1986; Duarte, 1991). Increased turbidity caused by eutrophication, chronic upstream erosion and periodic dredging has dramatically reduced light penetration in many estuarine water columns, thereby reducing the depth distribution, density and productivity of these submerged macrophytes (Zieman, 1975; Orth and Moore, 1983; Cambridge and McComb, 1984; Shepherd *et al.*, 1989; Larkum and West, 1990; Zimmerman *et al.*, 1991; Monroe *et al.*, 1992).

In recent years, state and regional governments have begun to shift management emphasis from monitoring environmental deterioration to promoting the improvement of coastal zone water quality so that critical macrophyte-based ecosystems can be maintained and even expanded (Dennison *et al.*, 1993). Water management agencies in the State of Florida (USA) have developed a network of water-quality monitoring stations that include regular measures of submarine photosynthetically-active radiation (PAR) in an effort to protect and manage critically important seagrass resources (Steward and VanArman, 1987; Steward *et al.*, in review). There is, however, no reliable light-driven model of seagrass productivity to establish requirements for the nature and frequency of such data acquisition, or for the interpretation of irradiance data as it relates to impacts on growth, depth distribution and production.

Calculations of light-limited distribution and growth in submerged aquatic vegetation (SAV) usually follow some modification of the critical depth concept initially proposed by Sverdrup (1953). Stated simply, populations cannot persist in light environments where metabolic demand (respiration + growth) exceeds photosynthetic production. Current evidence suggests that seagrasses generally do not penetrate deeper than the isolume corresponding to 10% of the in-water surface irradiance, I_0 (Dennison & Alberte, 1986; Zimmerman *et al.*, 1989; Duarte, 1991). Persistence in some environments appears to require isolumes as high as 30% of I_0 (Onuf, 1991; Tomasko and Dunton, 1991; Dennison *et al.*, 1993). The critical depth concept based on mean irradiances, however, may be a misleading oversimplification with regard to resource management because patterns of depth distribution can become very complicated in environments with a high degree of temporal variation in photosynthetic photon flux (PPF) (Zimmerman *et al.*, 1991).

Although the temporal complexity of estuarine light environments has been underappreciated generally, attempts have been made to incorporate the structural complexity of seagrasses (vascular plants) into carbon budget calculations beyond simple leaf P:R ratios (Dennison and Alberte, 1982), to more realistic calculations that include the demand of below-ground tissue (Zimmerman *et al.*, 1989; Fourqurean and Zieman, 1991; Kraemer and Alberte, 1993). These models have served critical research functions, but they are not yet sufficiently reliable for use as real-world management tools.

Regardless of the number of structural components included, all carbon budget models start with rates of production calculated from measures of PPF. The relationship between the growth or production and the daily integral of light intercepted by the leaf canopy can be linear (Charles-Edwards *et al.*, 1986). This is usually not true, however, for total incident PPF because of the non-linear response of photosynthesis to PPF (Blackman, 1905). Numerical integration, the iterative summation of photosynthesis vs irradiance (P vs. I) over time, provides more mechanistic reality and is not difficult in theory, but can be laborious computationally. It also requires essentially continuous measures of irradiance and accurate knowledge of the instantaneous P vs. I response of the species in question. The daily production integral can be approximated from maximum PPF at solar noon, termed I_m, if the daily pattern of PPF follows a simple sinusoid (Thornley and Johnson, 1990; McBride, 1992). This integral is computationally simpler than iterative numerical integration and requires only a single daily measure of I_m. Significant and large errors, however, can be introduced to the extent that the *in situ* pattern of daily PPF deviates from sinusoidal.

The non-linear relationship between photosynthesis and irradiance is also the basis for the computationally simple H_{sat} model (Evans, 1972; Dennison and Alberte, 1982, 1985). In this approach, daily carbon gain is calculated as the product of P_m (the maximum rate of irradiance-saturated photosynthesis) and the total time that PPF exceeds the irradiance required to saturate photosynthesis (I_k). H_{sat} can be integrated numerically from continuous measures of PPF, or calculated from I_m if the daily pattern of PPF follows a simple sinusoid (Zimmerman *et al.*, 1987). Whether integrated numerically over the day or computed from I_m, the H_{sat} model assumes $P = 0$ when $PPF < I_k$. This can lead to significant underestimation of daily carbon gain (Fourqurean and Zieman, 1991). As with the approximate integration of P vs. I, calculations of H_{sat} based solely on I_m can introduce significant errors when the daily pattern of irradiance is not sinusoidal.

Each of the methods for estimating daily carbon gain described above has some useful features and some drawbacks. The reliabilities of the different methods, however, have never been compared using a single data set encompassing temporal variation in PPF sufficient to resolve the differences in accuracy among them. Increasing the biological sophistication of carbon budget models can be justified only when the effects of temporal fluctuations in PPF have been determined accurately. In this study, the effects of variation in PPF on the estimate of SAV production in a temperate estuarine environment was examined using five different models. The goal was to develop guidelines for the acquisition and use of irradiance time series data to predict the dynamics of production in SAV communities for resource management programs as well as more basic ecological studies.

METHODS

Photosynthesis vs. Irradiance Relationships

Vegetative shoots of *Zostera marina* L. were harvested monthly between September 1991 and August 1992 from a subtidal meadow in the Elkhorn Slough National Estuarine Research Reserve, near Monterey Bay (36°49′ N, 121°44′ W). Rates of photosynthesis and respiration were measured polarographically on tissue segments cut from leaf #2 (second youngest) at 10 different PPFs (including darkness) produced by a Kodak slide projector and neutral density filters (Dennison and Alberte, 1986). Rates of O_2 production were converted to carbon fixation using a photosynthetic quotient (O_2:CO_2) of 1.2. Data were fit to two commonly used non-linear models (Jassby and Platt 1976) using a direct fitting algorithm and error estimation procedure (Zimmerman *et al.*, 1987):

$$P = P_m \cdot \tanh (I/I_k) \qquad (1)$$

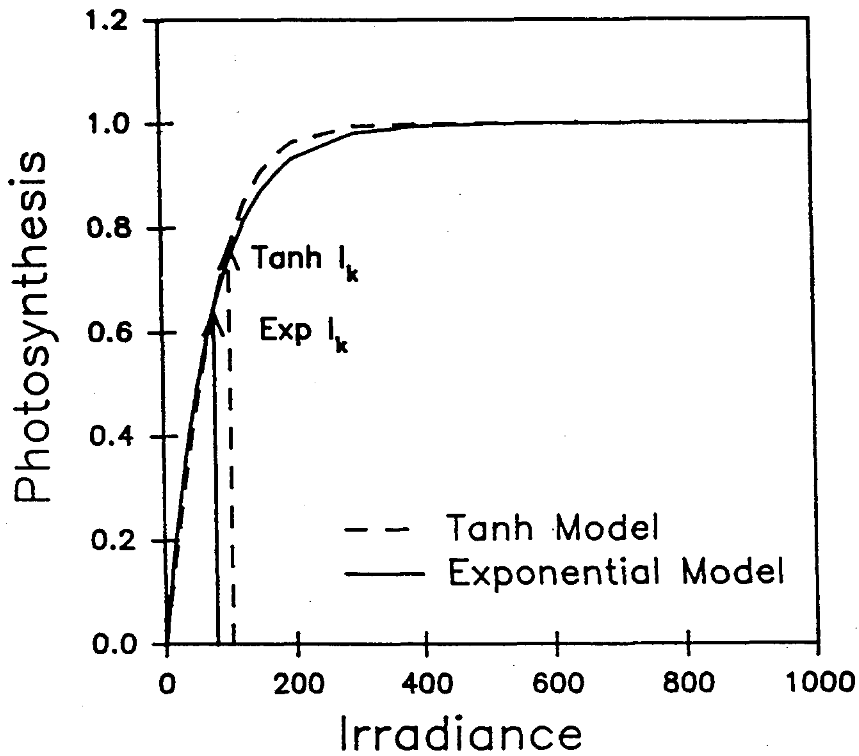
$$P = P_m \cdot [1\text{-}\exp(-I/I_k)] \qquad (2)$$

where P_m defines the maximum (or asymptotic) rate of photosynthesis and I_k determines the threshold for irradiance saturation of photosynthesis. Values of P produced by equations (1) and (2) differ by a maximum of 4.8% (Fig. 1). The value of I_k defined by Eq. (1), however, is 33% higher than defined by Eq. (2). Although this difference in I_k produces a trivial difference in the estimate of P from a given value of I (McBryde, 1992), it can have a significant effect when I_k is used as a direct parameter in the daily integration of P (see below). Complete presentation of seasonal variation in the P vs. I relationships of this eelgrass population are detailed elsewhere (Britting, Zimmerman and Alberte, in prep.).

IRRADIANCE TIME SERIES OBSERVATIONS

Time series of PPF were recorded using a pair of spherical (4π) quantum sensors (LiCor Model 193SA). The sensors were deployed permanently in an unvegetated spot adjacent to the seagrass bed to avoid shading by the leaf canopy. One sensor was placed at the sediment surface, while the other was located 0.5 m above the first at a height equivalent to the top of the shoot canopy. The PPF was recorded from both sensors at 15 min intervals using a LiCor Model 1000 data logger. Diffuse attenuation coefficients (K) were calculated according to Beer's Law using the difference in PPF measured by the two sensors only between 1000 and 1400 h each day to minimize the upward bias in K caused by low sun angles (Kirk, 1983; Miller and McPherson, 1993). The sensors were cleaned by SCUBA divers and the data logger was cycled every 14 d. Accumulation of fouling between cleanings, although visible on the sensors, had no measurable effect on recorded values during the 14 d periods, as evaluated by the difference in instantaneous PPF immediately before and after cleaning.

Figure 1. Hypothetical P vs. I curve demonstrating the ability of the tanh and exponential models to predict P from a given value of I. Although the curves follow very similar trajectories, the value of I_k generated from the tanh model is 33% higher that I_k derived from the exponential model.



For the purpose of the calculations presented below, irradiance was assumed to be constant during each 15 min interval and the PPF measured by the upper sensor was assumed to represent the light field experienced by a seagrass canopy. Development of a realistic carbon budget model for SAV ultimately will require the integration of light absorption by the canopy, leaf age distribution and sunflecking on rates of whole-plant photosynthesis (see Mazzella and Alberte, 1986), but those issues serve as unnecessary complications for the comparisons presented below.

ESTIMATES OF DAILY NET PHOTOSYNTHESIS

Daily production calculated from the iterative summation of P vs. I was independent of the formulation used because instantaneous predictions of P from I are virtually identical for Eqs. (1) and (2). Thus, the numerically integrated values of daily production generated from Eq. (1) were assumed to be the best obtainable, and were used as a benchmark against which the other models were evaluated. Parameters (P_m and I_k) for both Eqs. (1) and (2) were adjusted monthly according to metabolic rate measurements performed in the laboratory. Numerical integrations of P, calculated from Eq. (1), were fit to daily integrated PPF using a non-linear, direct-fit estimation routine in the NONLIN package of SYSTAT (Wilkinson, 1990). The temporal scale of decorrelation for the time-series of numerically integrated daily P was determined by calculating product-moment autocorrelation coefficients (r) for 10 bins of data (10-20 d each) using lags of 1-4 d.

Daily production was also calculated by approximating the time-integral of Eq. (1). The PPF (I) was assumed to be a sinusoidal function of time (t) since sunrise:

$$I = I_m \cdot \sin(\pi \cdot t/D) \qquad (3)$$

where I_m was the PPF at solar noon recorded by the upper sensor and D was the length of the daily photoperiod. Substituting for I in Eq. (1), P became a function of time of day (t):

$$P = P_m \cdot \tanh\left[\frac{I_m}{I_k} \cdot \sin\left(\frac{\pi - t}{D} \right) \right] \qquad (4)$$

The daily integral of P was then approximated by polynomial expansion when analytical integration of Eq. (4) proved to be impossible:

$$\int_{t=0}^{D} P\,dt = P_m \cdot D \cdot (-.0038 + 0.71x - 0.20x^2 + 0.0060x^3 + 0.0085x^4 - 0.0019x^5 + 1.8X10^{-4}x^6 - 8.2X10^{-6}x^7 + 1.4X10^{-7}x^8 \qquad (5)$$

This relation was valid over the domain $0 \le x \le 20$, where $x = (I_m/I_k)$. Photoperiod length (D) was adjusted daily assuming a sinusoidal function with a mean of 12 h (D =

12 h on the vernal and autumnal equinoxes) and an amplitude of 2 h (D = 14 h on the summer solstice, 10 h on the winter solstice):

$$D = 12 - 2 \cdot \cos\left(2\pi \cdot \frac{\text{Julian Date} + 10}{365}\right) \tag{6}$$

As before, the values of P_m and I_k were adjusted monthly, based on the polarographic P vs. I measurements.

Values of H_{sat} were calculated by two methods. In the first case, daily values were integrated numerically by summing the 15 minute time intervals in which I exceeded I_k each day, analogous to the numerical integration of P vs. I. In the second case, H_{sat} was estimated according to:

$$H_{sat} = D \cdot \left[1 - \frac{2}{\pi} \cdot \sin^{-1}\left(\frac{I_k}{I_m}\right)\right] \tag{7}$$

Like Eq. (5), this model assumed PPF to be sinusoidal function of time since sunrise (Figure 2). The PPF recorded by the upper sensor at solar noon was used for determining I_m. Daily production estimates were then calculated as $P_m \cdot H_{sat}$ for both methods. The H_{sat}-based calculations ignore those periods when P is a linear function of I ($I<I_k$), and therefore, will tend to underestimate daily production. As with the polynomial integration of P vs. I (Eq. 5), production estimates were then determined from daily records of I_m, monthly measures of I_k and P_m, and daily adjustments of D as described above.

RESULTS

IRRADIANCE TIME SERIES OBSERVATIONS

The high frequency variation in daily integrated PPF was so great in Elkhorn Slough that no obvious seasonal pattern was observed (Figure 3a), even though there is a predictable seasonal amplitude in day length of 4 h and maximum PPF (in air) of almost 1000 $\mu E\ m^{-2}\ s^{-1}$ at this latitude. There were, however, periodic events of extremely low PPF that lasted from 1 to 10 d. The longest of these events was caused by turbidity associated with a particularly rainy period in February and March 1992. Other extreme attenuation events of short duration (1-2 d) were generally associated with sediment loading and resuspension from storms and spring tides.

Daily means of the coefficient of diffuse attenuation (K) measured between 1000 and 1400 h were also highly variable, but there was some suggestion of a seasonal pattern (Figure 3b). The attenuation coefficient was most variable from December to March, corresponding to the rainy season. During this period, winter rains were responsible for episodic runoff that greatly increased the load of suspended particles in the water column of Elkhorn Slough. In addition, the spring low tides that also resuspend sediments occur during the afternoons in winter, complicating the temporal pattern of variation in K.

Figure 2. Diagrammatic representation of H_{sat}, as defined for a cloudless day. According to this definition, $P = 0$ when $I < I_k$.

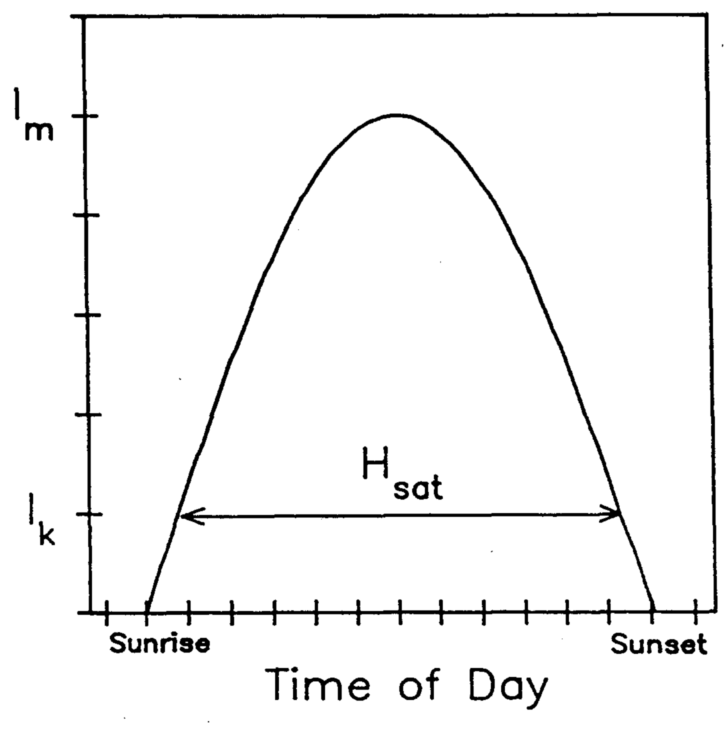
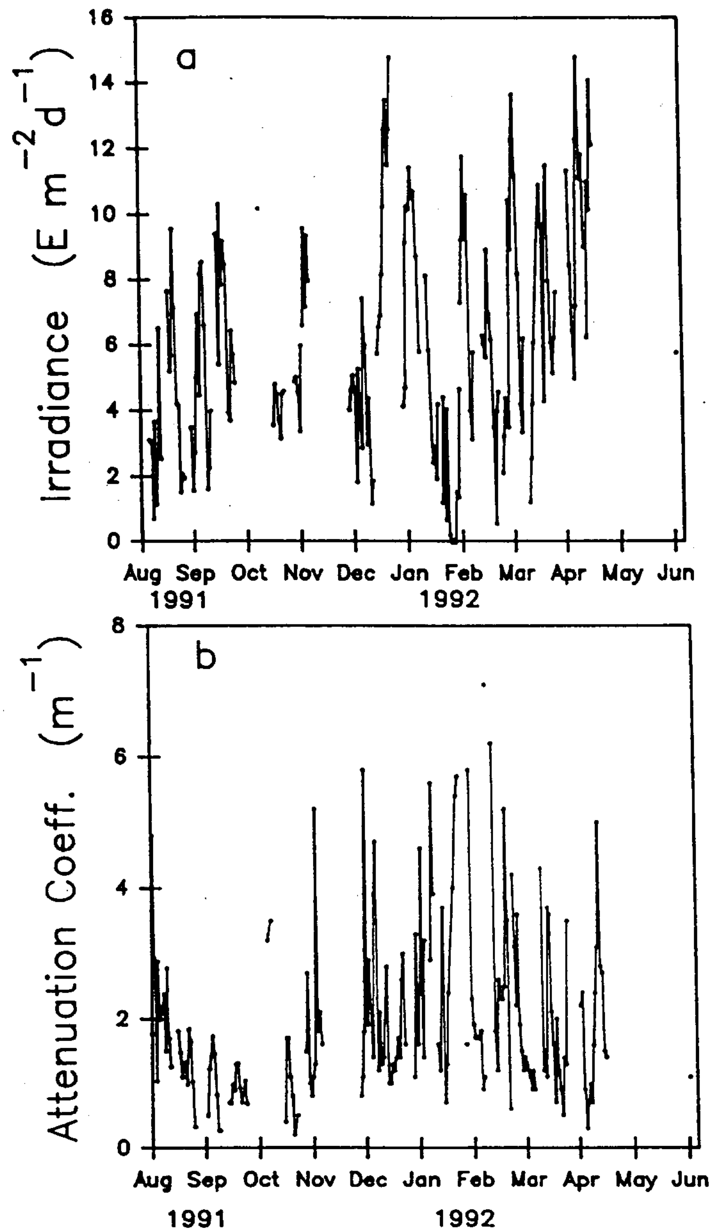


Figure 3.

(a) Time series of daily integrated irradiance at the Elkhorn Slough study site. Although there was a high degree of variation in daily photosynthetic photon flux, no seasonal pattern was evident from these data.

(b) Time-series of diffuse attenuation coefficient (*K*). Day-to-day variations were most dramatic during the winter rainy season.



ESTIMATES OF DAILY NET PRODUCTION

The variability in PPF produced a similar degree of variability in the time-series of daily integrated production. As with the light data, there was no obvious seasonal pattern (Figure 4a). In addition, there was virtually no autocorrelation in the time-series (Figure 4b). The mean correlation coefficient (r) for ten 10-d bins of data was a statistically insignificant 0.48 ($n = 10$, $p > 0.05$) when the data were lagged by only 1 d.

Increased lag periods resulted in even lower correlation coefficients. Clearly, this lack of temporal autocorrelation was caused by the high degree of day-to-day variability in PPF, likely typical of most estuaries.

The relationship between numerically-integrated production and numerically-integrated daily PPF was strongly nonlinear, and could be described by Equations (1) or (2), the same formulations as the instantaneous P vs. I response curve (Figure 5). Even though all of the irradiance time-series data were used in summing both daily P and daily PPF, the predictive reliability of this model was poor ($r^2 = 0.53$), especially when daily quantum flux was above 4 E m^{-2} d^{-1}.

Polynomial integration of P (Eq. 5), based on a single daily measure of I_m, also proved to be unreliable (Figure 6). Correlation with the numerical integral of daily P was not sufficiently strong for the polynomial estimate to be useful as a predictive model (Table 1). In addition to the unacceptably high degree of residual uncertainty (r^2= 0.71), daily estimates of production were upwardly biased by an average of 59 μmol C gfw^{-1} h^{-1}, relative to the numerical integration of Eq. (1).

In contrast, daily rates of primary production calculated from numerical integration of H_{sat} showed a strong linear correlation to the production rates generated by numerical integration of P vs. I ($r^2 = 0.92$). When I_k was estimated from Eq. (1) to calculate H_{sat}, the regression slope was essentially 1, but the negative intercept indicated a downward bias (underestimate) of 40 μmol C gfw^{-1} d^{-1} in the calculation of daily P (Figure 7a, Table 1). Daily P was estimated to be zero on 8 (5% of the time) of the 171 d when PPF never rose above I_k (and H_{sat} was undefined). Agreement between the numerically-integrated H_{sat} calculation of daily P and the numerical integration of P vs. I increased when H_{sat} was calculated from I_k determined by exponential model of Eq. (2) (Figure 7b). As with the tanh model (Eq. 1), the slope of the regression line was

Figure 4.

(a) Time series of daily production calculated from numerical integration of the tanh P vs. I model, using continuous recording of irradiance.

(b) Autocorrelation coefficient plotted as a function of lag period (days) for ten 10-d bins of numerically integrated production data. Error bars indicate 95% confidence limits of the mean for each lag. With n = 10, r must exceed 0.58 to be statistically significant at p = 0.05.

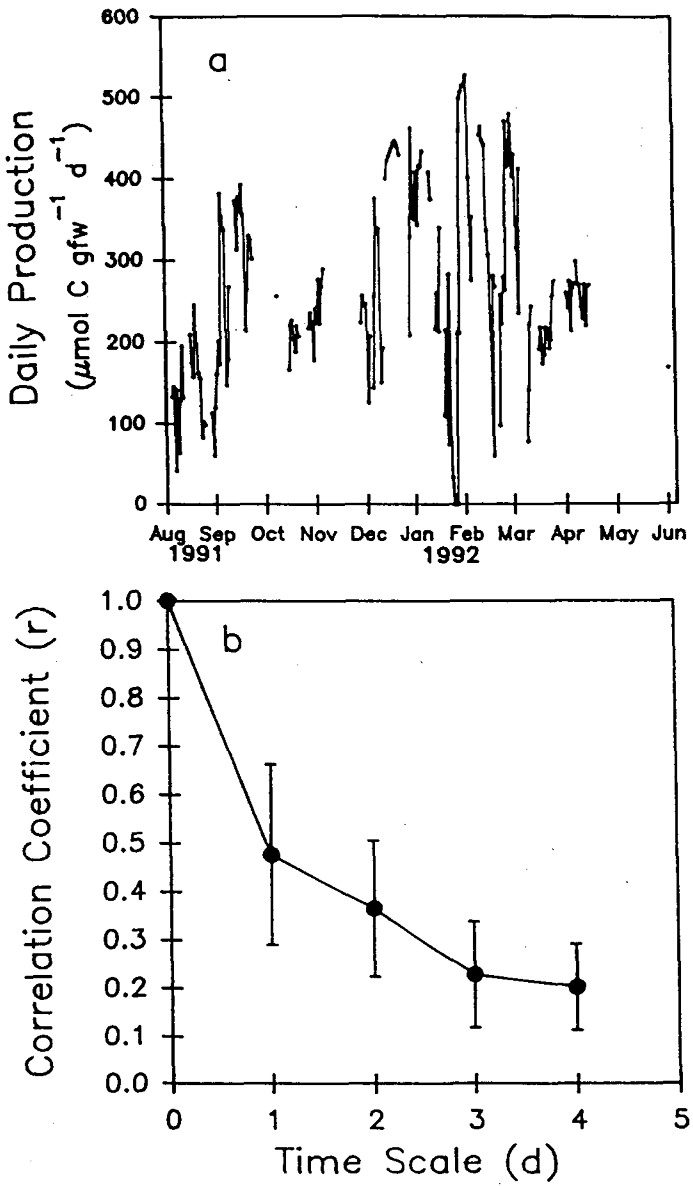


Figure 5. Integrated daily production plotted as a function of integrated daily PPF. The relationship was strongly nonlinear, but the high degree of scatter in the production data made this relationship unreliable for predicting daily carbon gain, especially when PPF exceeded 4 E m^{-2} d^{-1}.

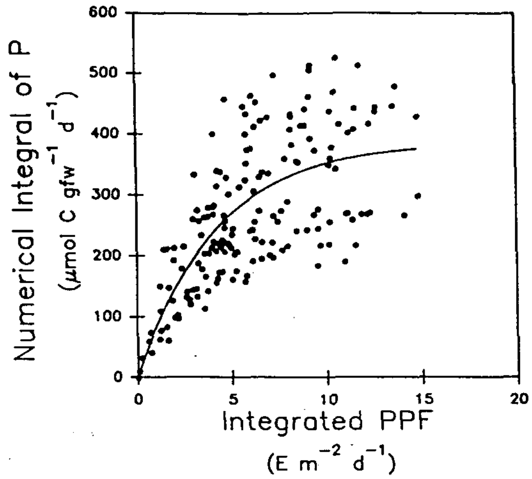


Figure 6. Daily production estimated by polynomial integration plotted as a function of numerically integrated P. Solid line represents perfect agreement between the 2 measures (slope 1, intercept = 0), while linear regression results are indicated by the dashed line.

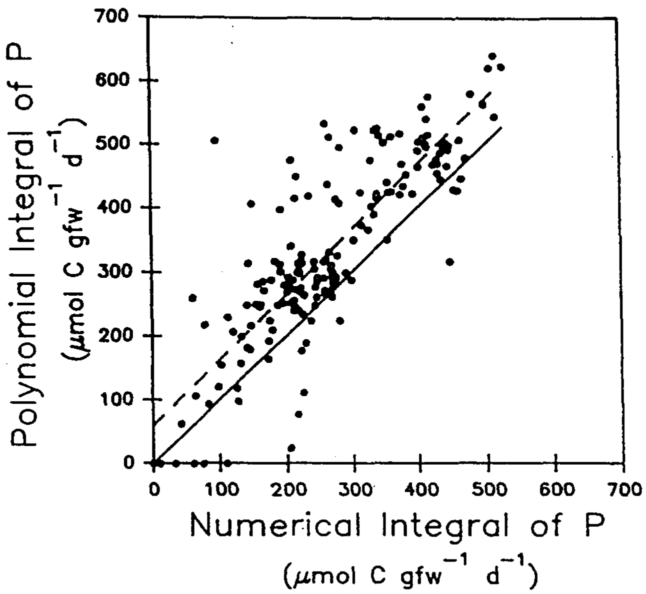


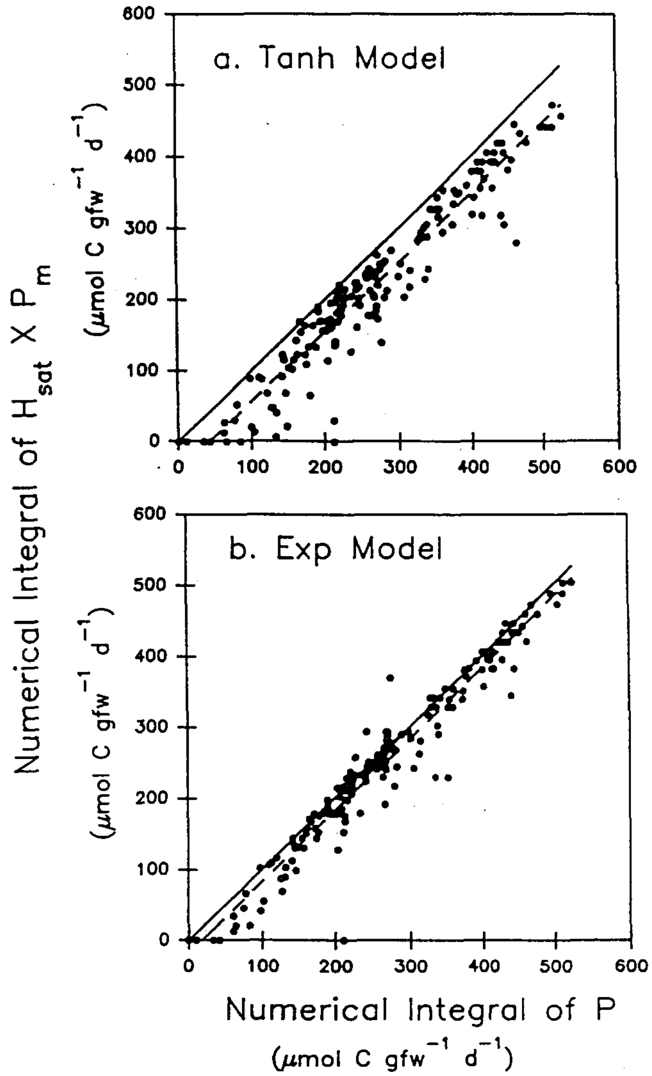
Table 1. Regression parameters from comparisons of production estimates plotted in Figs. 5-8. Confidence intervals of slopes and intercepts are presented as standard errors.

Independent Variable	Dependent Variable	Slope	Intercept	r^2	df
Numerical Integral of P	Polynomial integral of P	1.03±0.05	59±78	0.71	169
" " "	Numerical integral of P				
" " "	H_{sat} (tanh model)	0.97±0.02	-40±36	0.92	169
" " "	H_{sat} (exp model)	1.00±0.02	-17±30	0.94	169
" " "	Theoretical integral of H_{sat}				
" " "	tanh model	1.09±0.07	-13±108	0.59	169
" " "	exp model	1.11±0.06	19±99	0.64	169
Polynomial integral of P	Theoretical integral of H_{sat}				
" " "	exp model (all data)	1.09±0.02	-48±45	0.92	169
" " "	only data >200 μmol C gfw^{-1} d^{-1}	0.99±0.004	-3±6	0.997	141
" " "	tanh model (all data)	1.09±0.03	-83±60	0.87	169
" " "	only data >200 μmol C gfw^{-1} d^{-1}	0.98±0.01	-28±21	0.96	131

Figure 7.

(a) Daily production calculated from numerical integration of H_{sat} (tanh model) plotted as a function of numerically integrated P.

(b) Daily production calculated from numerical integration of H_{sat} (exponential model) plotted as a function of numerically integrated P. Solid lines in both cases represent perfect agreement between the plotted measures (slope = 1, intercept = 0), while linear regression results are indicated by the dashed lines.



not significantly different from 1. There was a slight improvement in the overall correlation ($r^2 = 0.94$) relative to the tanh model, and a considerable upward shift in the y-intercept such that the underestimate of daily production was reduced by 58% (Table 1). H_{sat} was undefined (and therefore $P = 0$) on only 6 (4% of the time) of the 171 d included in the analysis.

As with the polynomial integral, estimating daily P from Eq. (7) and a single measurement of I_m proved to be inaccurate, regardless of the formulation of I_k (Figure 8). The number of days when H_{sat} was undefined increased to 30 (18% of the time) and 19 (11% of the time) using values of I_k calculated from Eqs. (1) and (2), respectively. Regressions against the numerical integration of P vs. I were not as reliable as when H_{sat} was integrated numerically using the complete set of irradiance data collected each day (Table 1). Increased scatter in the H_{sat} estimates of daily P obscured the presence of systematic biases in the relationships, but in the case of both P vs. I models, the residual errors were sufficiently large to preclude the practical application of single PPF measurements for the calculation of H_{sat} values and daily production rates.

Although production estimates based on a single daily value of I_m were not very reliable predictors of daily P, the H_{sat} estimates of production showed remarkable agreement to the estimate obtained from the polynomial integral of P (Figure 9, Table 1). Serious disagreement between the two methods occurred only on very low-irradiance days when I_m remained near I_k, and H_{sat} approached 0. The tanh formulation of I_k, however, consistently underestimated daily P and showed less overall agreement to the numerical integration of daily P than the exponential formulation. Agreement between the polynomial and exponential estimates was virtually perfect for values of daily $P \geq 167$ µmol C gfw^{-1} d^{-1}. Thus, the exponential formulation of I_k should be preferred when applying the H_{sat} model to rates of daily production.

DISCUSSION

Most aquatic light monitoring programs, as currently implemented, focus on the collection of irradiance data for the calculation of water column attenuation coefficients (*K*), and stations are visited on weekly time scales at best (Dennison *et al.*, 1993; R. Viernstein, pers. comm). Unfortunately, the high frequency variations in light attenuation observed here probably are typical of coastal estuarine environments where water column turbidity is affected by physical and biotic factors. Processes

Figure 8.
(a) Daily production estimated from theoretical approximation of H_{sat} (tanh model) plotted as a function of numerically-integrated P.

(b) Daily production estimated from theoretical approximation of H_{sat} (exponential model) plotted as a function of numerically-integrated P. Solid lines in both cases represent perfect agreement between the plotted measures (slope = 1, intercept = 0), while linear regression results are indicated by the dashed lines.

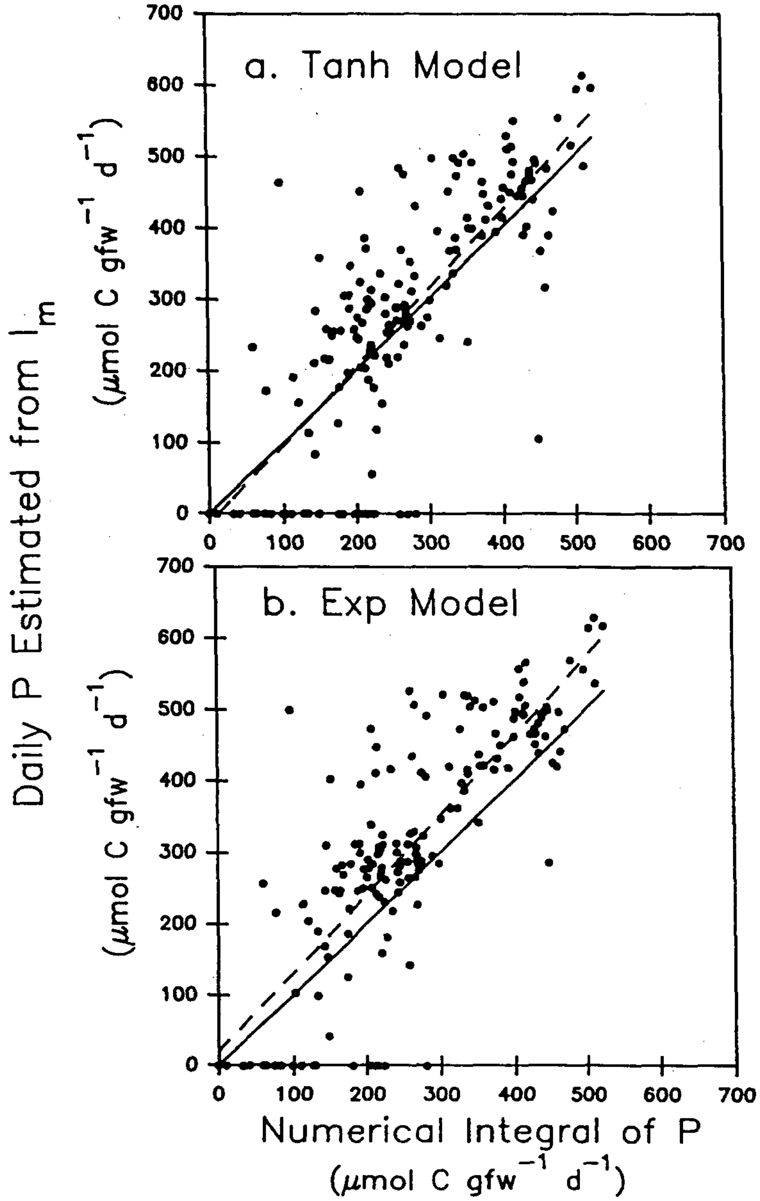
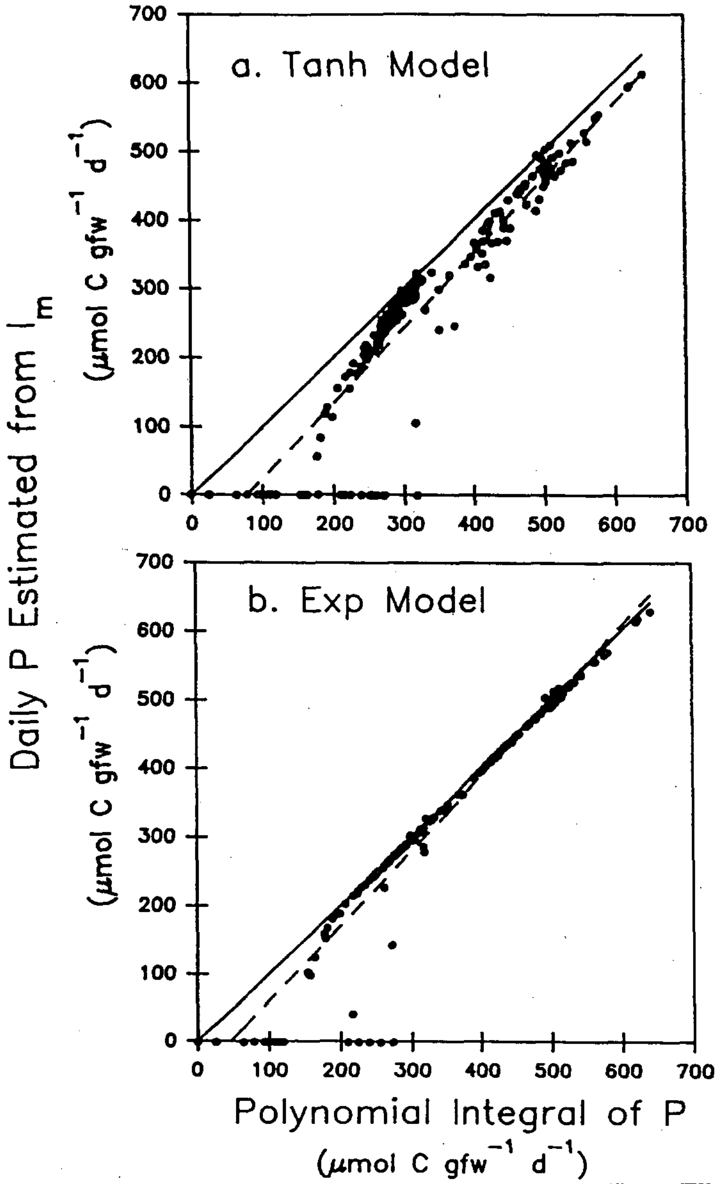


Figure 9.
(a) Daily production estimated from theoretical approximation of H_{sat} (tanh model) plotted as a function of the polynomial integral of P.

(b) Daily production estimated from theoretical approximation of H_{sat} (exponential model) plotted as a function of the polynomial integral of P. Perfect agreement between the plotted measures (slope intercept = 0) is represented by solid lines, while linear regression results are indicated by the dashed lines.



such as wind and tidal mixing, storm runoff and phytoplankton blooms combine to produce pulses of turbidity with chaotic periodicity. In this study, the time scale for autodecorrelation in daily integrated P was on the order of 1 d. Physiological parameters (P_m,I_k, etc.) of *Z. marina* changed from month to month (Britting, Zimmerman and Alberte, in prep.), but variation over the whole year was minimal when compared to the daily changes in irradiance. Furthermore, the biological parameters (P_m and I_k) were held constant within any given month for the calculations presented here. Thus, temporal fluctuations in PPF were the overwhelming source of variation in these data. Clearly, the only way to resolve such temporal variation in the irradiance signal is to record PPF at a high frequence.

The diffuse attenuation coefficient (*K*) calculated from Beer's law is commonly used to predict habitat suitability for SAV (Dennison *et al.*, 1993). In practice, *K* is usually assumed to be a "quasi-inherent" optical property of the water column, enabling the effects of atmospheric scattering and sun angle to be ignored (Kirk, 1983). Although this assumption may be valid in relatively clear and deep oceanic water (Siegel and Dickey, 1987), it does not necessarily hold in shallow and turbid estuarine environments. For example, solar angle alone can cause *K* to vary as much as 50% in shallow estuarine water column of Tampa Bay (Miller & McPherson, 1993). Thus, time of day becomes a critical component of the sampling program if the management/research goal is to estimate PPF at any depth in the water column. Continuous measures at a minimum of 2 depths will be required to resolve accurately the temporal variation in both incident PPF and *K* for many applications. If the data are to be applied primarily to production of SAV, then sensors should be placed at the primary depths of interest, and extrapolations to other depths using *K* should be performed with caution.

Numerical integration of P vs. I clearly provides the best estimate of daily carbon gain, assuming accurate estimates of PPF can be obtained. Although the daily integral of PPF may provide a relative index of irradiance availability, it did not provide a very accurate estimate of daily carbon gain in this case, even though it was also calculated from continuous recordings of PPF. Reliable determination of daily carbon gain of SAV, therefore will require accurate parametrization of the P vs. I response. Since P is calculated directly from each measure of PPF, the precise formulation of P vs. I is not very critical. Statistical uncertainty in parameter values, however, will be propagated in the repeated calculation of P vs. I. Thus, basic ecological studies of whole-plant carbon budgets should devote some effort to resolving the frequently observed high degree of biological variation in space and time (e.g. Fourqurean and Zieman, 1991) that can otherwise render meaningless the estimate of daily carbon gain.

Numerical integration of H_{sat} provided an excellent first order approximation of daily P when I_k was determined from the exponential model (Eq. 2). This is because low values of I_k produced longer daily H_{sat} periods, thereby increasing daily estimates of P. Although I_k is operationally defined as the irradiance required to saturate photosynthesis, the mathematical definition of I_k is considerably different and subject to variation based on the formulation of P vs I. For example, when $I = I_k$, $P = 0.76P_m$ with the tanh model (Eq. 1) and $P = 0.63P_m$ with the exponential model (Eq. 2). Overall, the calculation of H_{sat} was easier to perform than repeated evaluation of P vs. I, but the ready availability of personal computers and spreadsheet software significantly reduces the computational burden of the numerical techniques. Furthermore, numerical integration of H_{sat} requires continuously recorded PPF and the same P vs. I data to parameterize I_k as the direct numerical integration of P vs. I. Unlike the numerical integration of P vs. I, the H_{sat} estimate was sensitive to the value of I_k and therefore, the formulation of P vs. I.

Both polynomial integration and H_{sat} proved to be very poor predictors of daily carbon gain when based only on daily noon PPF. This is unfortunate because these methods involve fewer overall calculations which minimize rounding errors and the propagation of statistical uncertainty in parameter values associated with iterative methods. Furthermore, very few environmental monitoring programs have implemented continuous recordings of PPF, but could estimate I_m from reliable estimates of *K* and environmental climatology data. The utility of such low frequency (days-weeks) measures of diffuse attenuation for monitoring SAV productivity, however, has not been rigorously established for most sites. The results presented here strongly indicate that measures performed at these low frequencies would be of little value in the temperate estuary studied here or in other coastal environments that typically experience large excursions in water column light attenuation with chaotic periodicity (e.g. Zimmerman *et al.*, 1991).

The theoretical integration models (Eqs. 5 and 7) could be of value in environments characterized by more predictable changes in PPF. Although the polynomial model may have a slight advantage over the H_{sat} model because it does not become undefined at low irradiances, changes in PPF are probably not sufficiently predictable in most marine or estuarine environments to employ these models. In high irradiance environments where one might expect a single value of I_m to be adequate, the agreement between H_{sat} (using I_k derived from the exponential model) and the polynomial integral was remarkably exact. Calculation of H_{sat}, furthermore, is a bit less cumbersome than the 8th order polynomial needed to approximate the daily integral of P. Thus, problems in predicting daily carbon gain from H_{sat} (Fourqurean &

Zieman, 1991) have less to do with the square-wave nature of the model's definition than in the inappropriate application of Hsat to extremely low-light environments. Although this study was carried out in an extremely turbid estuary (*K* values can exceed 6.0), H_{sat} was undefined less than 10% of the time. Careful application of the H_{sat} model was also able to provide very good first approximations to the daily integral of P in comparison to both the numerical and polynomial integration of P vs. I.

The concept of H_{sat} may have significant ecological implications to SAV beyond daily carbon gain because it may affect carbon transport and anoxic stress in root tissues anchored in permanently flooded sediments. In fact, aerobic metabolism of root tissues in *Zostera marina* depends directly on photosynthetic oxygen production by the leaves (Smith *et al.*, 1984). The roots of *Z. marina* appear to be remarkably tolerant of prolonged anoxia providing there are ample carbohydrate supplies to support energy production and growth (Smith, 1989; Kraemer and Alberte, 1993). Root anoxia, however, blocks acropetal sucrose transport in eelgrass (Zimmerman and Alberte, in prep.), as it does in many vascular plant species (Geiger and Sovonick, 1975; Jackson and Drew, 1984; Saglio 1985). Thus, H_{sat} may provide useful indices of the daily period of root aerobiosis, sucrose transport and carbon partitioning in seagrasses. These issues will become more important as growth models develop more mechanistic detail and improved predictive capacity.

It appears that accurate determination of daily carbon budgets for SAV will require continuous records of PPF. Single daily measures of quantum flux were inadequate to estimate daily carbon gain with an acceptable degree of precision in Elkhorn Slough. Thus it is extremely unlikely that measures of PPF made on weekly or monthly time scales will be of any ecological utility unless the environment is very predictable, in which case PPF probably could be estimated from geophysical theory (see Kirk, 1983). Obviously estuarine environments are the last places one would look for such stable environments (Miller and McPherson, 1993).

In recognition of the difficulty in measuring light availability, depth distributions of SAV have been proposed as low-technology barometers of estuarine habitat quality (Dennison *et al.*, 1993). If the management goal is to reverse the loss of SAV by improving water clarity, use of SAV as "miner's canaries" seems inappropriate. Thus, model comparisons made here and other investigations (Zimmerman *et al.*, 1991) demonstrate that submarine light availability must be measured with greater temporal and spatial resolution than is currently implemented by most environmental monitoring programs. This will necessitate the exploitation of recent advances in electronic technology that now enable field sites to be permanently instrumented with continuously recording light monitoring equipment, as it is extremely unlikely that reliance on manual measurement of PPF or water column light attenuation will generate useful data sets for scientific or management purposes.

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DEFINING THE ECOLOGICAL LIGHT COMPENSATION POINT OF SEAGRASSES IN THE INDIAN RIVER LAGOON

by

W. Judson Kenworthy, Ph.D.
Beaufort Laboratory
NMFS, NOAA
Southeast Fisheries and Science Center
Beaufort, NC. 28516

INTRODUCTION

Estimating the minimum light requirements of seagrasses is an important step in developing an optical water quality model for predicting the impact of water quality on the distribution and abundance of seagrasses. An optical water quality model allows for prediction of seagrass cover based on known light attenuation coefficients, estuarine bathymetry and a compensation depth (Dennison *et al.*, 1993). A comprehensive model predicts the percentage of surface light reaching depth, based on commonly measured water quality parameters such as chlorophyll, total suspended solids and water color (Gallegos and Correll, 1990; Gallegos *et al.*, 1991; Gallegos, in press). Water depths corresponding to the percent of surface light required by aquatic vascular plants defines the compensation depth and the bottom area potentially suitable for habitation by seagrasses. In this form an optical water quality model would also identify the parameters most influencial in determining the penetration of light. A key to the use of this modeling approach for the development of water quality criteria is a quantitative understanding of the compensation depth for the seagrasses of interest.

Because most seagrasses have a large amount of non-photosynthetic tissue growing in anaerobic sediment, measurements of leaf photosynthesis alone cannot be used to estimate a light compensation point (Zimmerman *et al.*, 1989; Kenworthy and Haunert, 1991; Fourqurean and Zieman, 1991; Kraemer and Alberte, 1993). Alternatively, simultaneous measurements of the maximum depth to which seagrasses grow and an average light attenuation coefficient can be used to estimate the whole plant light compensation point (Dennison, 1987; Duarte 1991; Kenworthy and Haunert, 1991; Dennison *et al.*, 1993). Assuming the Lambert-Beer equation (eq. 1) describes the behavior of photosynthetically active radiation (PAR) in water, the percent of surface light corresponding to the maximum depth of seagrass growth can be estimated with the following equation.

$$I_z = I_o \cdot e^{-kz} \tag{1}$$

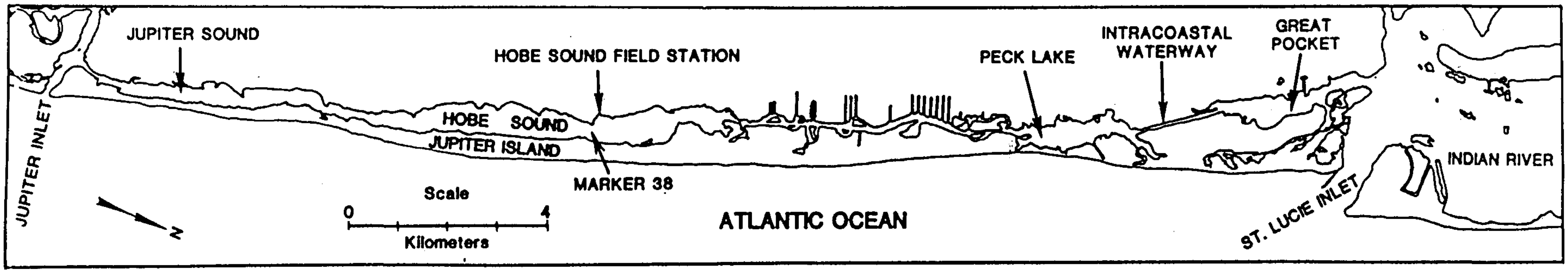
where; I_z = underwater quantum irradiance at depth z in umol m^2 sec^{-1}
I_o = underwater quantum irradiance at 10 cm depth in umol m^2 sec^{-1}
z = depth at I_z
k = diffuse PAR light attenuation coefficient or k_d (m^{-1})

This percentage value (e^{-kz}) approximates the plant's minimum light requirement and together with bathymetry information a simple model can predict whether seagrasses will grow on a depth contour (Dennison *et al.*, 1993). The accuracy of this prediction will depend on the spatial and temporal variability of the attenuation coefficient (k_d) as well as the sensitivity of the plant's response to k_d.

Morphological, physiological and life history differences between species are the likely reasons for a wide range of estimates for the maximum depth of growth (Duarte, 1991; Dennison, 1993; Kenworthy, 1992). In general, seagrass minimum light requirements fall within a broad range of values between 4.4 and 25 % surface light (Dennison *et al.*, 1993). Because small differences in estimates of the minimimum requirements can make large differences in predictions of bottom covered, it is critical to examine the variability in k_d and develop a comprehensive understanding of the plant response. This is especially true for estuaries and lagoons like the Indian River which have very gentle bottom slopes.

In this paper I report the results of a long-term study (3.5 years) evaluating the relationship between the maximum depth of seagrass growth in the southern Indian River and the average diffuse PAR light attenuation coefficient (k_d). The seagrasses I examined are the two dominant species in the Indian River Lagoon, *Halodule wrightii* and *Syringodium filiforme*. I also discuss the implications of light limitation relative to the distribution of *Halophila* species. Using a long-term data set of PAR attenuation I estimate the minimum light requirements of the seagrasses and examine the feasibility of using these as an estimate of the light compensation depth for an optical water quality model.

Figure 1. Illustration of the study site located in Martin County Florida. Primary study sites are Hobe and Jupiter Sounds.



MATERIALS AND METHODS

A. Study Site

The study site was located at the southern end of the Indian River Lagoon in Jupiter and Hobe Sounds, Lat. 27°02'30", Long. 80°04'00" (Figure 1). Tidal flow originates primarily from Jupiter Inlet and establishes an inlet to interior lagoon water transparency gradient (Kenworthy, 1992). The lagoon is stenohaline (30-35 ppt) with water temperatures ranging between 17 and 32° C. Average depth is between 1.75 and 2.00 m with a maximum depth of approximately 4.0 m.

B. Submarine Light Regime

Two water transparency data sets were evaluated in this study. The first data set was more intensive, consisting of a weekly sampling of 24 stations located on six shore-normal transects (four stations per transect) spaced nearly evenly apart from north to south in Hobe Sound. This data set was obtained between March 1987 and November 1988 and was reduced to 16 stations on 4 transects between November 1988 and September 1990. The second data set was more extensive and originated from a transect established along the stem channel axis of the Intracoastal Waterway from Jupiter Inlet (south) to the north end of Hobe Sound. Nine stations on the stem channel axis located 1.3, 4.0, 5.9, 6.6, 7.5, 9.1, 10.1, 11.7, and 13.3 km from Jupiter Inlet were sampled on approximately a weekly basis between March 1987 and September 1990.

At each station a submarine light profile was obtained using a pair of LI-COR LI-193SA spherical quantum sensors. Sampling was scheduled for time intervals between 10 am and 2 pm to avoid periods when surface reflection and solar angle would alter the submarine light regime and estimates of attenuation. One sensor was maintained as a deck cell and a second sensor was immersed to a depth of 10 cm (I_o) as a reference for all further measurements in the submarine light profile (I_o). A submarine light profile consisted of 4-6 pre-determined measurements at nearly evenly spaced intervals not to exceed a total depth of 170 cm.

For computation of a PAR attenuation coefficient (k_d), I regressed the natural log transformed value of PAR at each depth interval against depth and calculated the slope of the reduction in PAR. This slope equals k_d PAR. Regressions with r^2 values less than 0.8 were discarded.

C. Seagrass Distribution.

Seagrass depth distribution and relative species composition were obtained from; 1) 196 shore-normal, shallow water benthic survey transects located 100 m apart along the longitudinal axis of Hobe (145) and Jupiter (51) Sounds, and 2) 92 shore-normal, deep water survey transects.

The shallow water transects extended from approximately mean tide level out perpendicular from shore (shore-normal) to just beyond the lower depth distribution of the two dominant species, *H. wrightii* and *S. filiforme*. The deep water shore normal transects (92) extended from the lower depth limit of the two shallow water species out 100 meters normal to the lagoon's shoreline axis to depths of 3.5 to 4.0 m.

The shallow water transects were spaced 100 m apart along the longitudinal axis of the lagoon. At each 5 m interval along an individual transect a SCUBA diver placed a 0.5m^2 PVC quadrat and recorded the macrophyte species present, the time, and the water depth. Water depths were normalized to a permanent tide station located at the Hobe Sound National Wildlife Refuge (Kenworthy,1992). Water levels at transect locations were adjusted using published time differences from reference stations in NOAA tide tables. Time differences were verified and calibrated at each sampling period. Shallow water transects were sampled in Hobe Sound in May 1989 and in both Hobe and Jupiter Sounds in August 1990.

The deepwater transects were sampled by two methods. The first method was designed to be exploratory in nature. In August 1989, February 1990, February 1991 and May 1991, predetermined transects, 2.7 m wide by 100 m long, were aligned perpendicular to shore. Location of these transects were based on the absence of a seagrass signature in 1/10,000 scale high resolution color aerial photos and confirmed by preliminary *in situ* observations (Kenworthy,1992). The aerial photos revealed a sharp contrast in signatures between what appeared to be relatively shallow vegetated bottom as opposed to no signature in relatively deeper water. *In situ* observations confirmed that the absence of a signature corresponded to the lower depth limits of *H. wrightii* and *S. filiforme* but not necessarily the absence of seagrasses. All three species of *Halophila, H. decipiens, H. johnsonii,* and *H. engelmanni* were observed growing in the deeper water during preliminary surveys in the spring and summer prompting a more detailed survey.

On the preliminary deep water transect survey in Hobe Sound, a SCUBA diver carried a 0.5 m^2 PVC quadrat fitted with one meter extensions on each side. The diver followed a transect tape and whenever the diver encountered a seagrass patch within the path delineated by the PVC device (2.7 m wide), the species present and the size of the patch(s) were recorded. The second deepwater sampling method utilized in August 1991 was modified from the shallow water method. Predetermined 100 m long transects were oriented perpendicular to shore in the same locations as the previous deep water transects. At 5 m intervals along the transect a diver placed a 1 m^2 PVC quadrat divided into sixteen 25 cm by 25 cm grids on the bottom. The number of grids vegetated and the species present were recorded to obtain percent cover. The time and water depth were also recorded.

D. Relationship Between Average Annual k_d Value and Maximum Depth Seagrass Growth

The ten deepest observations for maximum depth of growth of seagrasses (*H. wrightii* and *S. filiforme*) on the shallow water transects in each basin of the lagoon were averaged to get a mean depth of growth for a particular basin. The mean values for maximum depth of growth from basins corresponding to submarine PAR stem channel stations 1.3, 5.9, 7,5, 9.1, 10.1, 11.7 and 13.3 km from Jupiter Inlet were plotted against the average annual percent surface light computed by incorporating the k_d values into the Beer-Lambert equation. The relationship between average k_d value, percent surface light and maximum depth of growth were compared graphically.

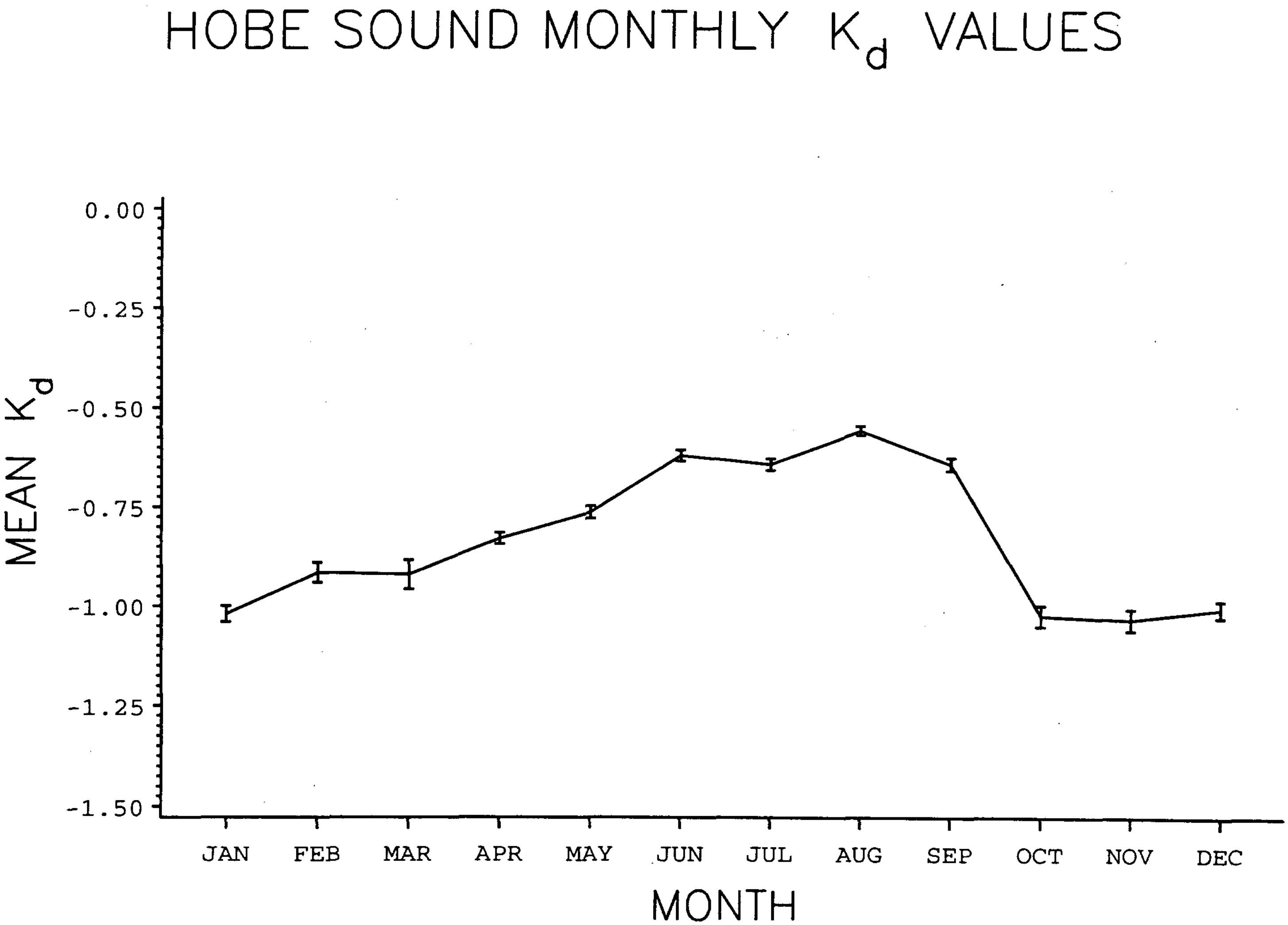
RESULTS

A. Submarine Light Regime

The monthly average k_d values for the 6 intensively sampled transects in Hobe Sound illustrate the seasonal fluctuation between relatively clearer summer k values (0.5 - 0.6) and less transparent conditions between the months of October and April (0.7 - 0.1) (Figure 2). These seasonal fluctuations were evident at each station, regardless of distance from the inlet (data not shown). The lagoon-wide annual average k_d value was 0.76.

The seasonal fluctuations and the overall lagoon average mask a significant spatial gradient that is illustrated by the results of the stem channel transect (Figure 3). Water transparency decreased (k_d increased) as a function of the distance from Jupiter Inlet.

Figure 2. Monthly average k_d values (+/- standard error) for all stations in Hobe Sound.



B. Relationship Between k_d Value and Percent Surface Light

As the average annual k_d value increased from 0.483 to 0.933 the maximum depth to which the larger species, *H. wrightii* and *S. filiforme,* grew on the shallow water transects decreased from 2.71 m to 1.06 m (Figure 4).

H. decipiens and *H. engelmanni* grew in water depths in excess of the maximum depth of the two larger species down to approximately 3.5 - 4.0 m. *H. engelmanni* was extremely rare yet perennial, while *H. decipiens* grew only in the clearer and warmer months between late April and November. *H. decipiens* appearead to be an annual with populations regenerated each growing season by seed (Kenworthy, 1992). *H. johnsonii* was rare but unlike *H. decipiens,* grew from the intertidal down to depths of approximately 3.0 m. Despite being low in abundance, *H. johnsonii* was perennial.

During the deep water sampling isloated long shoots (rhizome with 3-12 short shoots) of *H. wrightii* and *S. filiforme* were sparsely distributed in the deeper water areas beyond their maximum depth of growth on the shallow water transects. These long shoots did not appear to survive the winter (Kenworthy, 1992).

Estimated average annual percent surface light at the maximum depth of growth for *H. wrightii* and *S. filiforme* increased from 23 and 27% in the relatively clearer water of Jupiter Sound to 37% at the north end of the transect (Figure 5).

DISCUSSION

The maximum depth of growth for *H. wrightii* and *S. filiforme* decreased along the inlet to interior lagoon transect corresponding to an increase in k_d. However, both species grew to the same maximum depths (Kenworthy, 1992), suggesting that these two species have similar minimum light requirements. A previous study in the clear tropical waters around the island of St. Croix indicated that *S. filiforme* grew deeper than *H. wrightii* (Phillips and Lewis, 1983). These contrasting observations may be due to different growth response patterns in a seasonally fluctuating sub-tropical setting (Indian River Lagoon) versus the more continuous environmental conditions of the tropics (St. Croix), because *H. wrightii* has relatively faster asexual reproduction and areal coverage rates (Fonseca *et al.*, 1987). In a seasonally fluctuating light environment *H. wrightii* may be able to occupy as deep a depth as *S. filiforme* by taking better advantage of optimum growing conditions during shorter seasonal periods of clear water. Whereas in the more constant environment of the tropics, subtle growth

Figure 3. Average k_d values (+/- standard error) for all stations along the stem channel transect. k_d values are plotted as a function of distance in kilometers (km) from Jupiter Inlet.

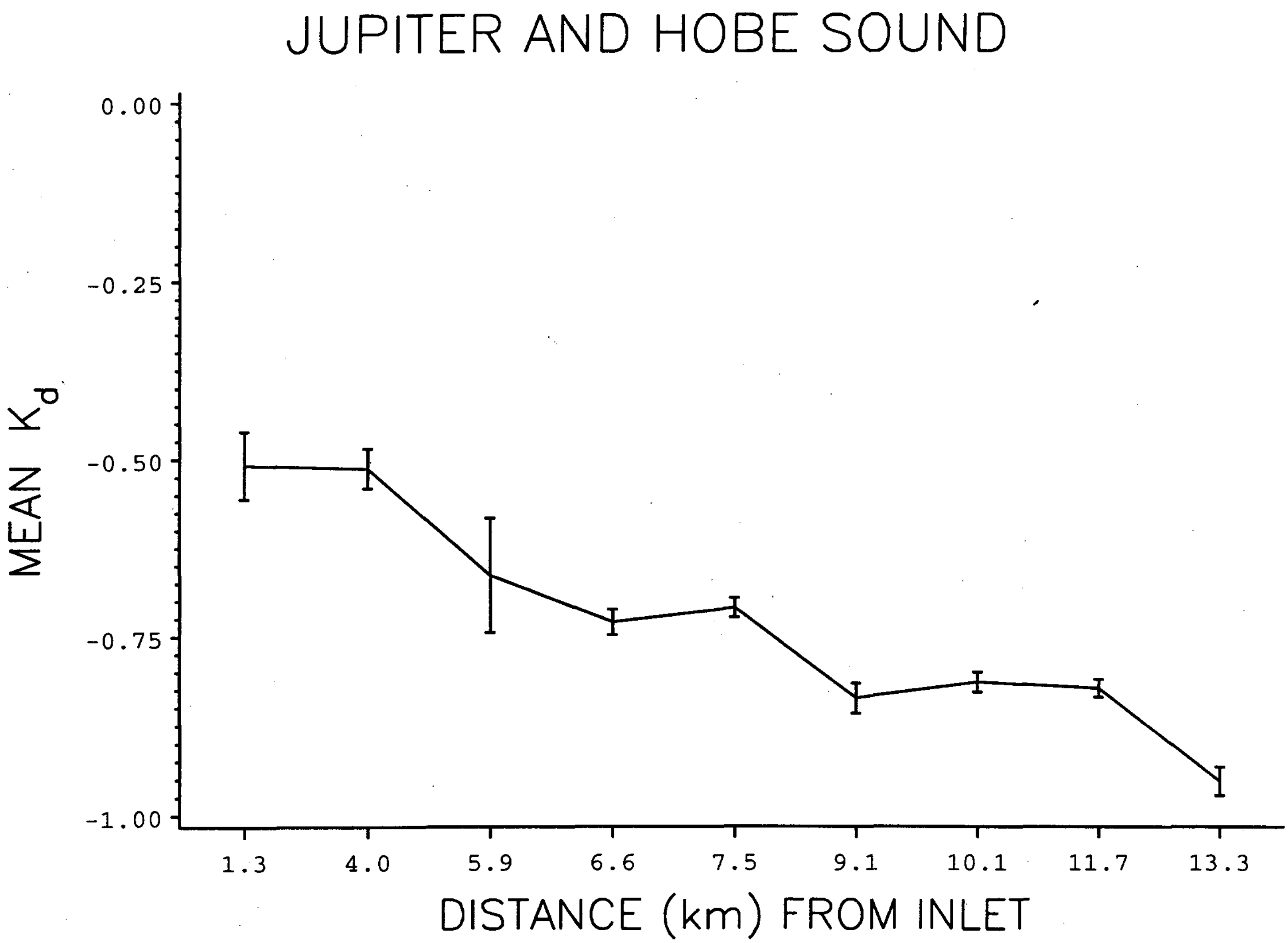
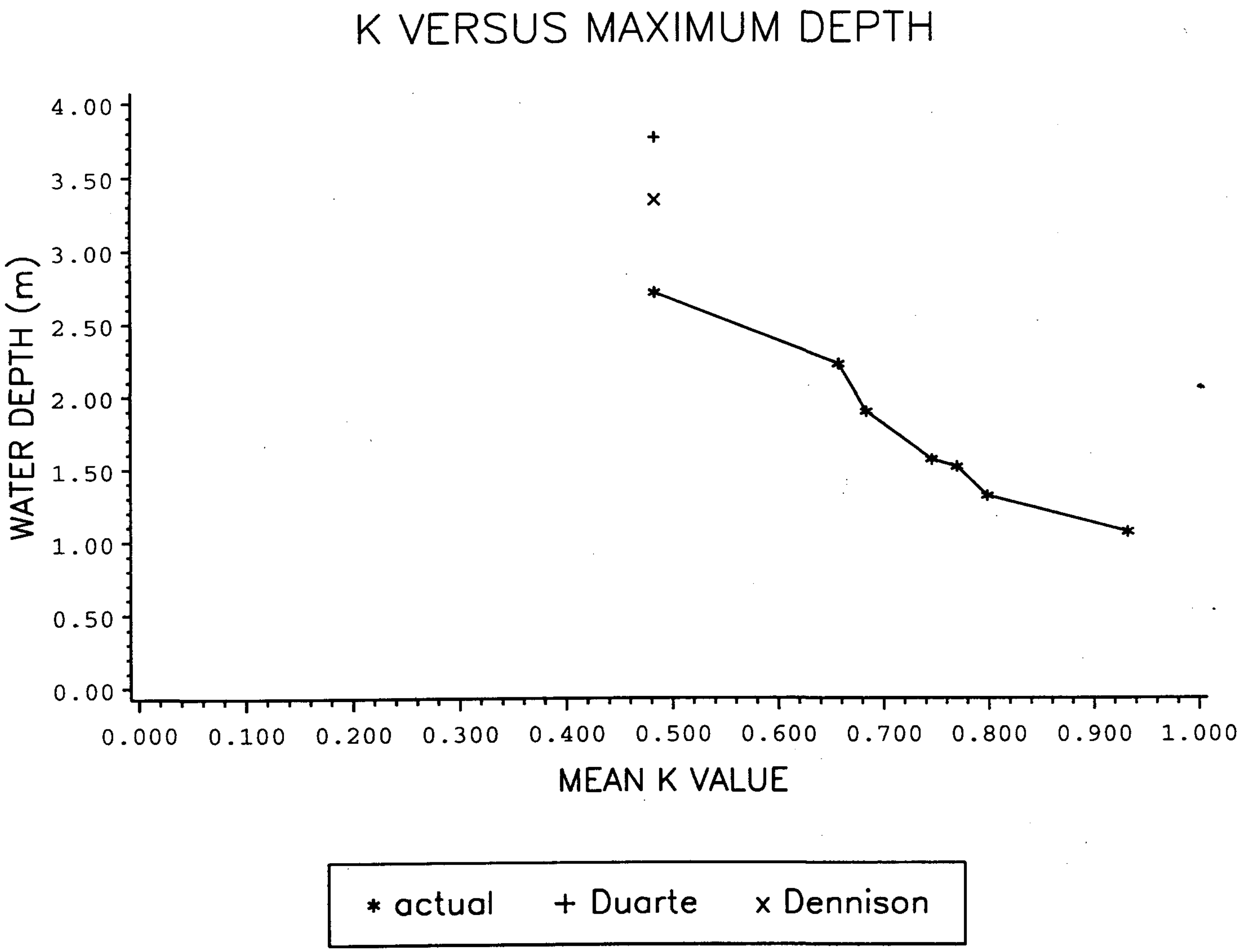


Figure 4. Average k_d values (+/- standard error) for all stations along the stem channel transect verses the maximum depth of seagrass growth. Also shown are predicted depths of growth from regression models developed by Dennison (1987) and Duarte (1991).



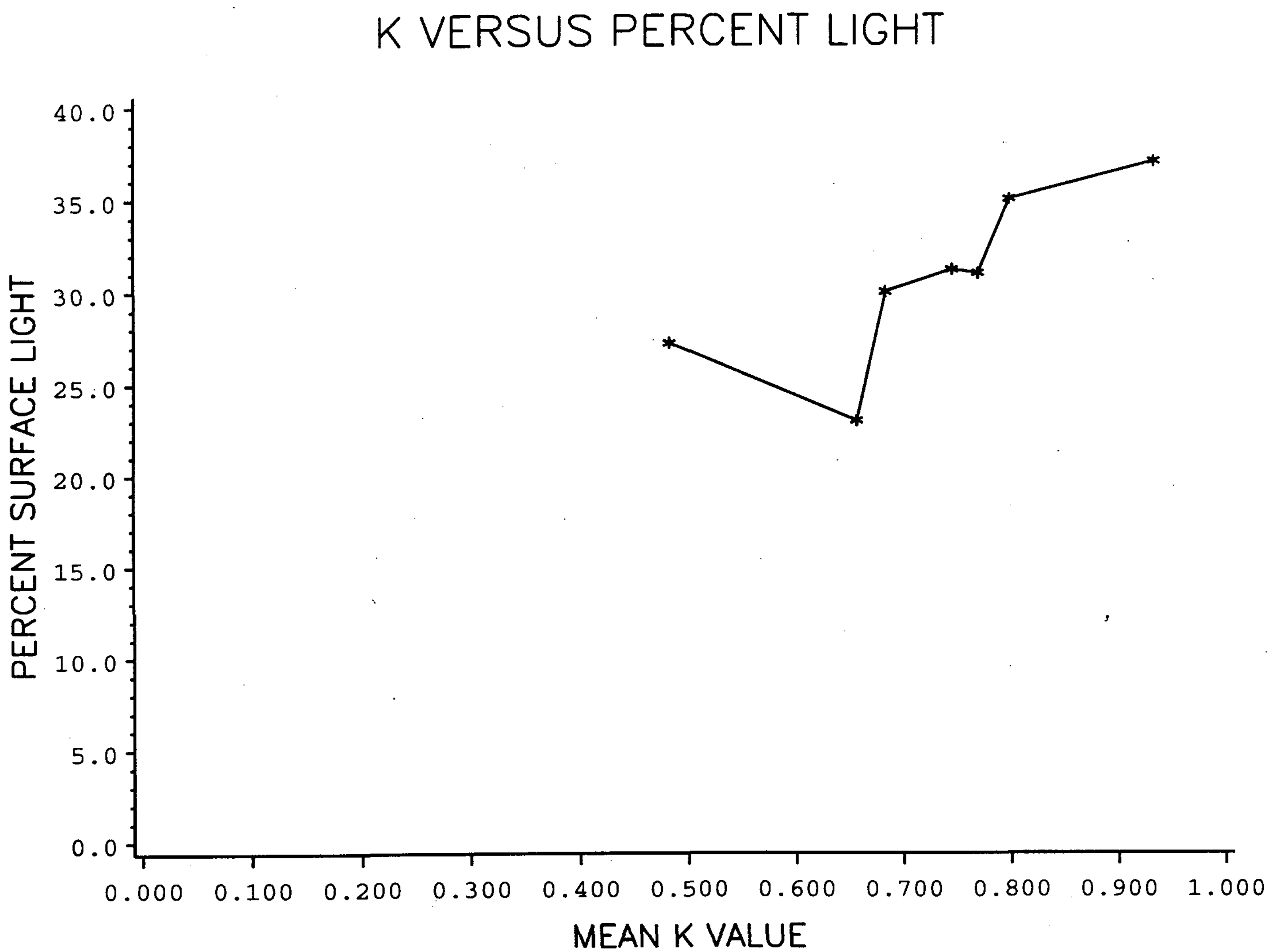
or physiological differences related to their light requirements could result in separate depth distributions over long periods of time, despite differences in population growth rates.

The maximum depth of seagrass growth corresponded closely to the declining PAR light attenuation coefficient (Figure 4). In general, the response pattern was similar to other seagrass species (Dennison, 1987; Duarte, 1991). However, prior to this study, specific values were unavailable for *H. wrightii* and *S. filiforme* growing in the Indian River.

Based on these average annual light attenuation coefficients and the maximum depth of growth, the estimates of percent surface light required for these two species varied along the transect (Figure 5). In the clear water of Jupiter Sound the minimum light requirements appear to be much less than in less transparent waters of Hobe Sound. These differences may actually be larger than illustrated here. The station closest to Jupiter Inlet with the clearest water also has the highest current velocities and least stable bottom sediments. Maximum depth of growth could be limited by water motion and the migration of unstable sand waves. Assuming this is true, and that seagrasses could grow deeper if water motion were not a factor, the percent surface light estimates for the Jupiter Sound station nearest the inlet were overestimated. Thus, differences in minimum light requirements along the transect would be even greater.

I tested this assumption by estimating the maximum depth of seagrass growth using the average annual k_d value at the clearest Jupiter Sound station and regression models developed by Dennison (1987) and (Duarte 1991). These two published models predicted seagrasses should grow to a depth much greater than depths observed at the Jupiter Sound (Figure 4), supporting my assumption that depth of penetration was limited by conditons other than light. This would indicate that percent surface light requirements (16-18%) are much less in Jupiter Sound than suggested by the actual field data and that estimated minimum light requirements along the 14 km transect range from as little as 16% to as much as 37%. This large a range would be unacceptable for estimating compensation depths in any type of model designed to predict the effects of changing water transparency on seagrass abundance. For example, typical bottom slopes in the Indian River are approximately 2 cm m^{-1} (Kenworthy, 1992). Assuming a condition where the light attenuation coefficient were 0.7 the predicted compensation depths based on 16 and 37% incident light would range from 1.65 to 3.05 m, respectively. Taking a single basin in the Indian River with a linear distance of 10 km and a typical slope (e.g., Hobe Sound and Jupiter Sound),

Figure 5. Plot of mean k_d values verses percent surface light.



the two estimates of compensation depth would result in a prediction of seagrass cover differing by approximately 700,000 m^2, or 169 acres. In this example the predicted deep edge of the bed would differ by about 70 m in linear distance.

If you examine the regression models developed by Dennison (1987) and Duarte (1991) nearly the same magnitude of variablity is present. The variation in these models suggest that the estimates of compensation depth by these methods would have limited application as a management tool. Alternatively, if the variation in these earlier models and in this current study could be explained, the information could be used to gain a more comprehensive understanding of the mininimum light requirements of seagrasses and improve the predictive capability of the models.

An alternative hypothesis explaining the different estimates of the minimimum light requirements along the stem channel transect is that different optical water quality characteristics varying along the transect are differentially influencing available PAR. Because of the nature of absorbtion by water molecules and dissolved constituents, the penetration of light in water is skewed toward relatively shorter wavelengths. Spectrally selective light attenuation by chlorophyll, suspended inorganic material or dissolved organic matter (color) may have a greater effect on theses wavelengths and may not be adaquately quantitatified by the broad band PAR quantum sensor. The mechanistic explanation postulated by this hypothesis is based on the absorption spectrum of chlorophyll and the action spectra of photosynthesis. Peak chlorophyll absorption spectrum occurs near the two ends of the visable spectrum; the blue (425-475nm) and the red (650-675nm) regions. Green, orange and red light (475-650nm) are absorbed only slightly. The action spectrum of photosynthesis is most sensitive to wavelengths around 450 and 650nm (Photosynthetically Utilizeable Radiation, PUR) and would be the wavelengths of PAR most likely attenuated along the stem channel transect where water molecules act to absorb the longer wavelengths and dissolved organic matter and suspended chlorophyll increase (Kenworthy, 1992). Differences in percent surface light requirements may then be explained by both quantitative attenuation of the total amount of PAR (k_d) as well as qualitative attenuation of shorter wavelengths not adequately detected by k_d alone. Although the quantum sensor can detect gross changes in PAR, it alone is not sensitive to detection of factors causing selective attenuation.

The implications for understanding the variation in minimum light requirements can be illustrated with an example of how a resource manager might utilize the model of k_d versus maximum depth of growth (Dennison *et al.*, 1993). Assume a discharge of colored water was proposed for a relatively clear estuary or lagoon similar to Jupiter

Sound. Initially we might assume that the observed k_d versus maximum depth of growth could be used to estimate minimum light requirements for the seagrasses in the lagoon. In this example we will be conservative, using the observed data and not adjusting the estimates based on the published models (Dennison, 1987; Durate, 1991).

Using the station nearest the inlet the current conditions in Jupiter Sound are; average annual k_d = 0.483, maximum depth of growth = 2.71m and percent surface light requirement = 27.0%. If we wished to predict the impact of the discharge on the abundance of seagrasses, a water quality and hydrodynamic model could be developed to estimate a scenario of different light attenuation coefficients (k_d), depending on the volume of discharge and the mixing characteristics of the water body. Ignoring the details of the complex hydrological model and simply examining the scenario of possible light attenuation values, the problem with using k_d can be demonstrated. Assume the hydrological model predicts a new k_d of 0.650. Using the Jupiter Sound model the Beer-Lambert equation predicts the depth of 27% surface light decreasing to 2.01 m. Therefore, we would predict that the maximum depth of growth would retreat about 0.6 m. However, it is likely that the new water quality conditions in Jupiter Sound, following the colored water discharge, would be more similar to the current conditions in Hobe Sound and the more approriate model would be derived from the relationship between k_d and maximum depth of growth in Hobe Sound. Assuming the conditions suggested by the station in Hobe Sound with a minimum light requirement of 35 %, the k_d value of 0.65 would predict a compensation depth contour of 1.61 m. This estimate is much less than 2.01 m calculated by the the Jupiter Sound model. The implications are that the impact of the discharge would be underestimated by using the relationship developed in Jupiter Sound alone. Likewise, predicting improvements in a turbid or colored water body using the model developed under the current conditions in Hobe Sound may underestimate the potential improvements in seagrass cover following an increase in transparency associated with a reduction in discharge.

In summary, the results of this study suggest that optical water quality models for predicting the effects of changing water quality on seagrass abundance must be calibrated under different combinations of water quality (e.g., color, chlorophyll, suspended materials). More importantly, if current condtions changed, the models must be refined so that predictions of seagrass response are matched with expected conditions. Although useful as a rapid and gross diagnostic tool for detecting changes in the submarine light regime (see Appendix II), k_d PAR alone cannot be used to develop precise estimates of minimum light requirements of seagrasses under different combinations of water quality. Qualitative aspects of light attenuation (PUR) may also be important in determining minimum light requirements for *H. wrightii* and *S. filiforme*.

ACKNOWLEDGEMENTS

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THE PHYSIOLOGICAL BASIS FOR RESPONSES TO LIGHT AVAILABILITY

by

David A. Tomasko, Ph.D.
Sarasota Bay National Estuary Program
1550 Ken Thompson Highway
Sarasota, FL 34236

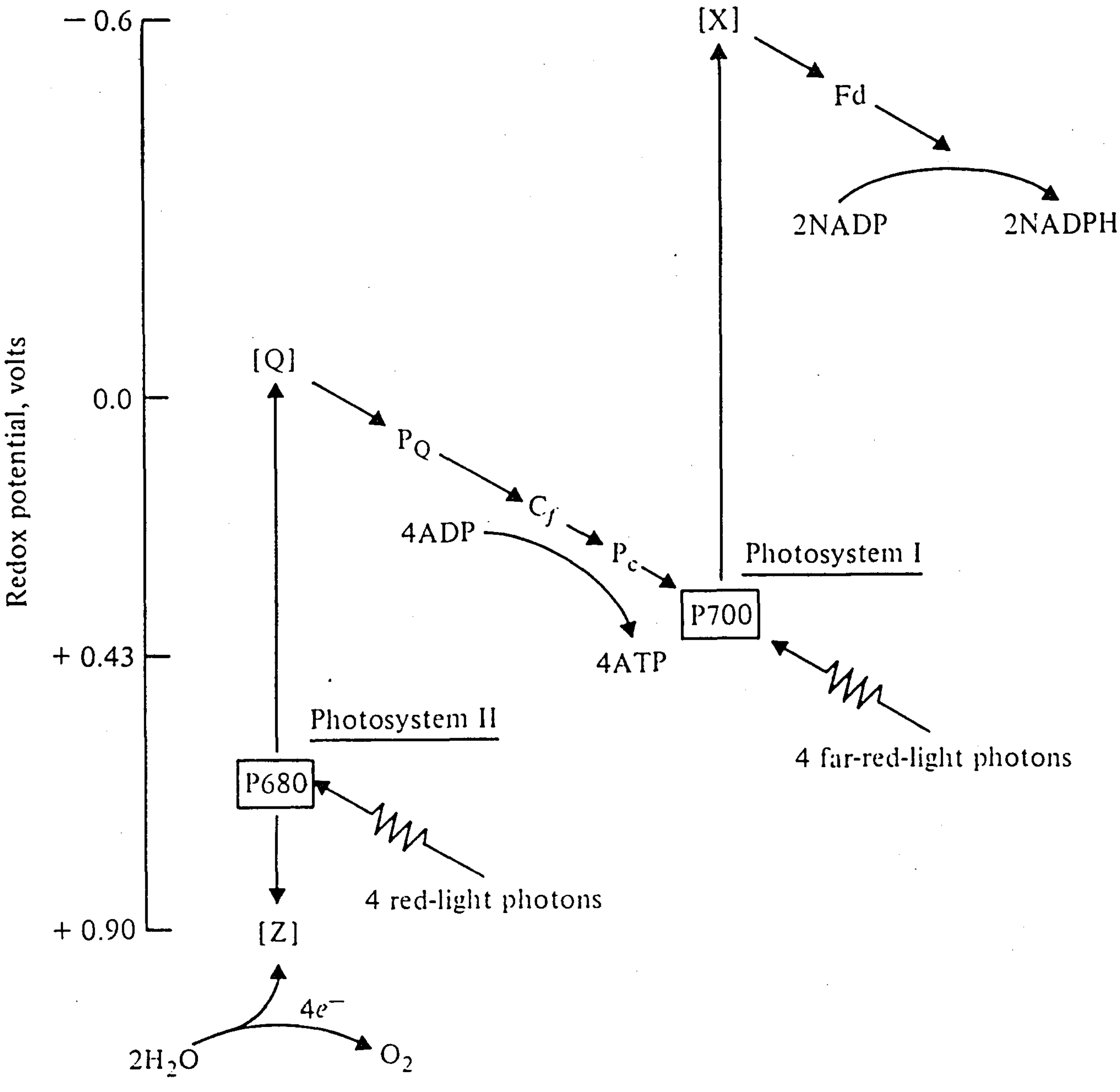
OVERVIEW

The availability of underwater light is a primary factor controlling the distribution, abundance, and productivity of seagrasses (see reviews in Dennison, 1987; Kenworthy and Haunert, 1991). The importance of underwater light relates to the central role of photosynthesis in converting radiant energy to chemical energy. The pigments of seagrasses, similar to the pigments of other plants, act to trap radiant energy and utilize that energy to reduce inorganic CO_2 to more complex organic molecules. These complex molecules can then be oxidized to release energy in a form more useful for cellular metabolism.

This chapter will focus on the photochemistry of photosynthesis, or the light-dependent reactions. Carbon metabolizing reactions, also called light-independent or dark reactions, will not be discussed, although they are integral to plant metabolism. The basic model of non-cyclic photophosphorylation, the Z-scheme, is illustrated in Figure 1. The end products of non-cyclic photophosphorylation, ATP and NADPH, are essential for cellular metabolism.

The electron transport chain is located within the thylakoid membranes. As electrons pass from carrier to carrier along the transport chain, protons are pumped from the chloroplast stroma into the intra-thylakoid space. The release of protons back into the stroma is then channelled through ATP synthetase and NADP reductase complexes, forming ATP and NADPH.

Figure 1. The Z-scheme for electron transport in photosynthesis (from Ting, 1982).



PHOTOSYNTHESIS-IRRADIANCE (P-I) RELATIONSHIPS

The basic relationship between photosynthetic rates and irradiance levels is shown in Figure 2. The terms of note for discussing P-I curves include I_c, alpha, P_{max}, and I_k. I_c stands for compensation irradiance, or the light level at which oxygen evolution from photosynthesis just cancels out oxygen demand from respiration. I_c values are traditionally restricted to blade metabolism, with the value I_{cp} reflecting whole plant oxygen balances. Alpha values quantify photosynthetic efficiency, and are expressed as photosynthetic rates per quanta of photons. P_{max} values express maximum photosynthetic rates, which can be either directly measured or determined by extrapolation from a model. I_k refers to the saturating irradiance level, which is determined by dividing Pmax by Alpha.

Photosynthetic parameters are measured with varying degrees of error. Calculated I_c values have not historically included non-photosynthetic biomass (i.e. Dennison and Alberte, 1982, 1985, 1986; Dennison, 1987; Dawes and Tomasko, 1988), thus compromising their ability to predict whole plant carbon balances. Newer studies have sought to address this problem by calculating a value for I_{cp} (i.e. Dunton and Tomasko, 1991; Fourqurean and Zieman, 1991).

Values for P_{max} can be determined directly by measuring photosynthetic rates above a certain light level (i.e. Dennison and Alberte, 1982, 1985, 1986; Dennison, 1987; Dawes and Tomasko, 1988), or they can be calculated by use of various P-I models (i.e. Dunton and Tomasko, 1991; Fourqurean and Zieman, 1991).

Calculations for I_k, which are usually determined by dividing P_{max} by Alpha, can give values obviously not "saturating" for photosynthesis. For example, Fourqurean and Zieman (1991) show that photosynthetic rates continue to increase at irradiance levels higher than calculated I_k values (see Table 2, and Figure 3 in Fourqurean and Zieman, 1991). In this and other instances, the value I_k is appropriately-derived mathematically, yet it is devoid of any meaningful physiological value. As I_k is used in conjuntion with measurements of underwater light levels to determine Hsat (hours of saturating irradiance per day; see Figure 3), the appropriateness of using any particular value for I_k needs careful consideration.

Figure 2. Hypothetical photosynthesis-irradiance (P-I) curve, illustrating P-I parameters (from Fourqurean and Zimmerman, 1991).

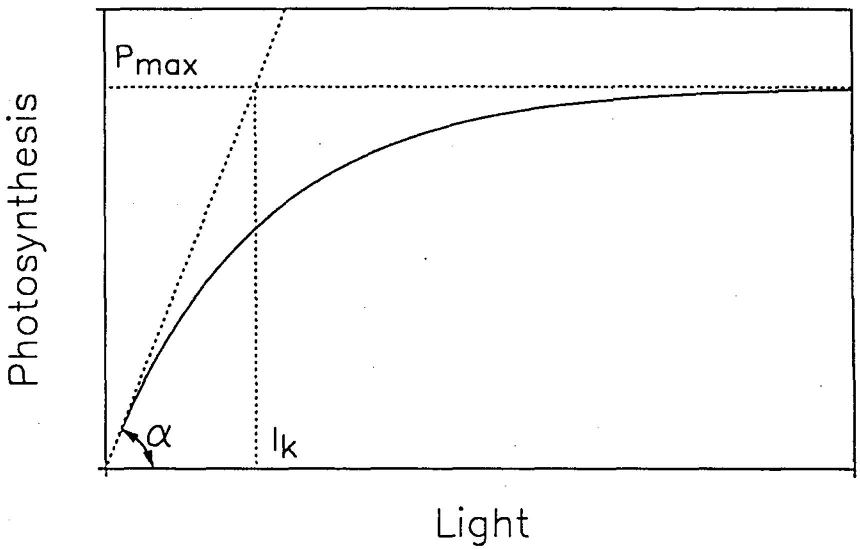
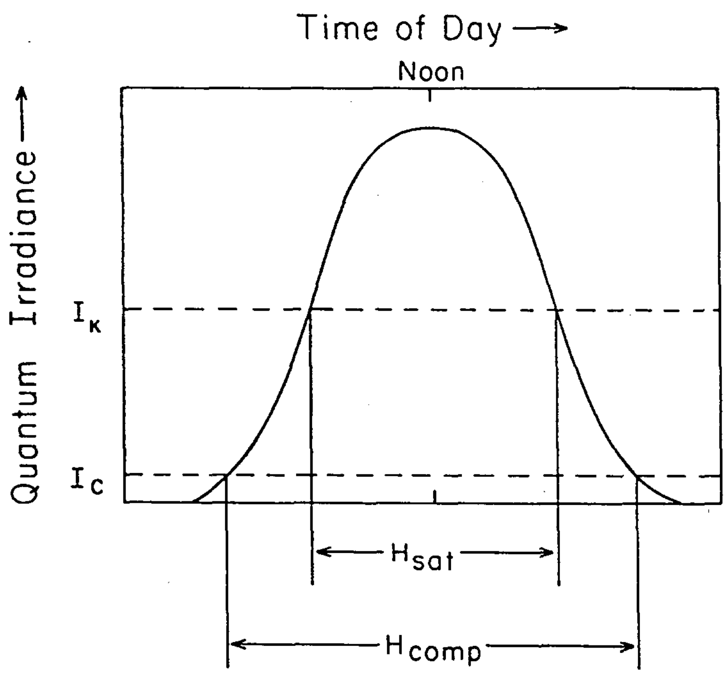


Figure 3. Hypothetical diurnal underwater light curve, illustrating the determination of H_{comp} and H_{sat} by use of I_c and I_k (from Dennison, 1987).



SPATIAL AND TEMPORAL CHANGES IN P-I PARAMETERS

Several studies have examined depth-related differences in P-I relationships (e.g. Drew, 1978; Dennison and Alberte, 1986; Libes, 1986; Pirc, 1986; Dawes and Tomasko, 1988). In general, most studies found a set pattern when comparing deep vs. shallow seagrasses; deeper plants had lower P_{max} values and higher blade chlorophyll values than their shallow counterparts. Typically, deep plants have shade-adapted P-I responses, while shallow plants have sun-adapted P-I responses (Figure 4).

Seasonal variation in P-I parameters have been examined by Drew (1978), Libes (1986), and Pirc (1986). In a manner similar to depth-related differences, seagrasses collected during times of the year with poor water clarity typically had lower P_{max} values and higher blade chlorophyll contents than plants collected during times of the year with better water clarity, although exceptions were shown to occur (Drew, 1978).

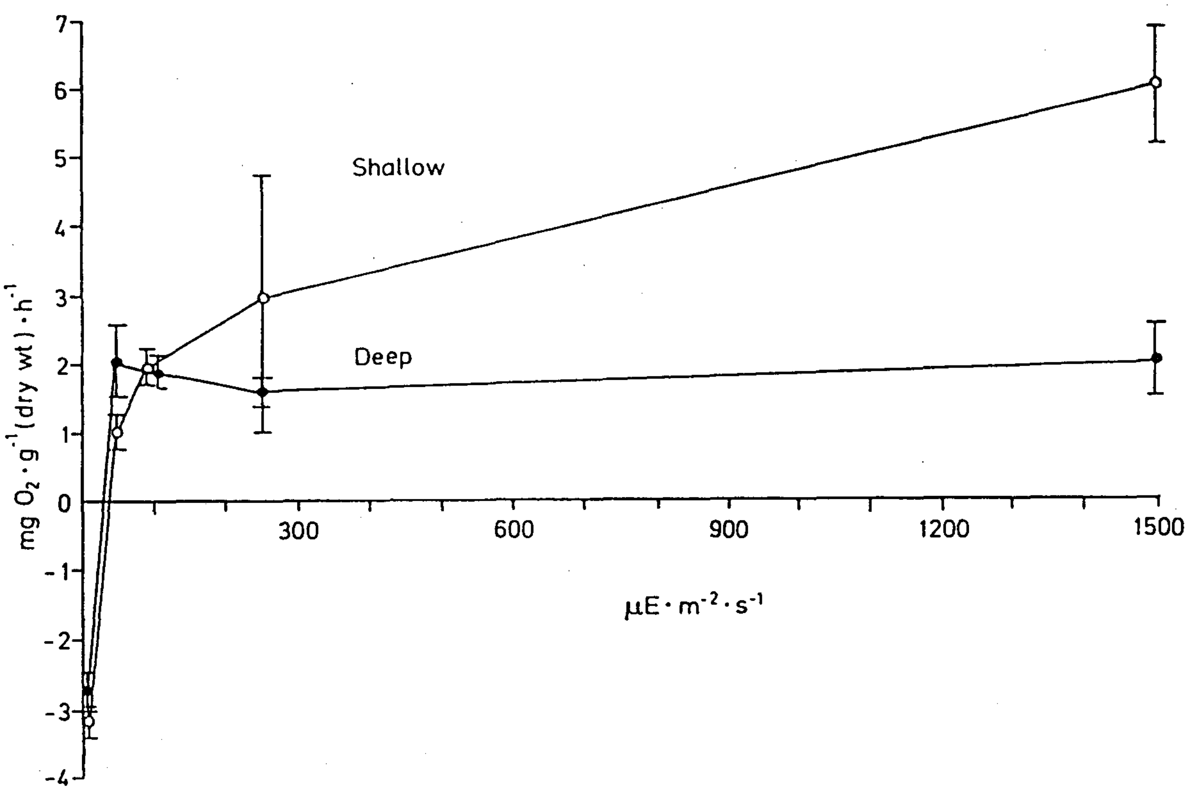
Adaptations to lower light, whether due to increased water depth or decreased water clarity, typically involve specific physiological adaptations. In many vascular plants, the increased leaf chlorophyll content associated with adaptation to low light is accompanied by decreases in the ratio between Chlorophyll *a* and Chlorophyll *b* (Baker and McKiernan, 1988). Such a response is thought to indicate that the increased abundance of Chlorophyll *b* is mainly due to increases in the size of the light harvesting complex associated with photosystem II (Baker and McKiernan, 1988). However, measured increases in blade chlorophyll contents occurred without any correlative changes in the Chlorophyll *a* : Chlorophyll *b* ratios in *Posidonia oceanica* (Drew, 1978), *Cymodocea nodosa* (Drew, 1978), and *Thalassia testudinum* (Wiginton and McMillan, 1979; Tomasko and Dawes, 1990).

CONCLUSIONS

Seagrasses have many physiological characteristics that allow them to adapt to the low light conditions typically found in many marine and estuarine locations. As light levels decrease, seagrasses typically respond by increasing their blade chlorophyll levels, mainly by increasing the concentrations of Chlorophyll's *a* and *b* in equal amounts. Increased chlorophyll levels can result in more efficient photosynthetic responses at low light levels, but evidence for this phenomenon is incomplete at this time (see Tomasko, this volume p. 55).

As P-I responses show great variability with both depth-related and seasonal differences in underwater light levels, the ability to extrapolate P-I parameters to other locations and/or times of the year is limited. Additionally, as values of I_c often do not reflect whole plant oxygen balances, and values of I_k can be without any real physiological connotation, these parameters should be carefully considered before using them to calculate H_{comp} or H_{sat} values.

Figure 4. P-I curves for *Thalassia testudinum* from shallow and deep edges of a meadow off Anclote Key, Florida (from Dawes and Tomasko, 1988).



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MODELING THE EFFECTS OF SOLAR ELEVATION ANGLE AND CLOUD COVER ON THE VERTICAL ATTENUATION COEFFICIENT AND THE FRACTION OF INCIDENT PHOTOSYNTHETICALLY ACTIVE RADIATION ENTERING THE WATER OF TAMPA BAY, FLORIDA

by

Ronald L Miller
and
Benjamin F. McPherson
U.S. Geological Survey
4710 Eisenhower Blvd, B-5
Tampa, Florida 33634-6381

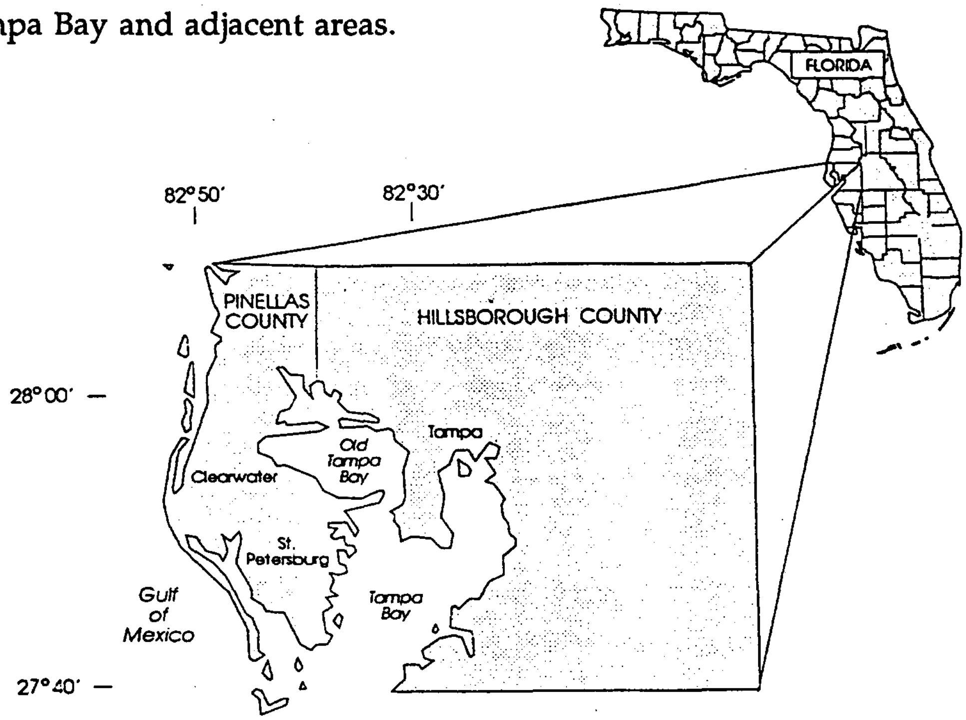
INTRODUCTION

Field studies that provide a comparison of the spatial and temporal variation in attenuation of light often neglect effects of solar angle and cloud cover, which can be significant. For example, if field sites are visited in the same order on each trip, spatial data can be biased due to the effects of solar angle. Even if sites are visited near solar noon, seasonal variations in the maximum solar elevation angle and cloud cover variation can have an influence on the vertical attenuation coefficient (k_0).

To correct for the effects of solar elevation angle and cloud cover, a model was developed that can be used to predict the amount and the average angle of photosynthetically active radiation (PAR) that enters and is transmitted through the water. The model uses solar elevation angle, an estimate of the relative amounts of diffuse skylight and direct solar beam, the attenuation coefficient, and the intensity of incident PAR irradiance. The calibrated model was used to estimate the daily variation in the vertical attenuation coefficient for scalar irradiance caused by different conditions of cloud cover, times of day, and times of year.

The study was supported by the U.S. Geological Survey and the Southwest Florida Water Management District through a jointly funded investigation.

Figure 1. Tampa Bay and adjacent areas.



METHODS

Data for model calibration consisted of 3,266 five-minute averages of incident and underwater PAR collected with 4π (spherical) sensors in Tampa Bay (Figure 1). The in-air sensor was mounted about 4 m above the water and shielded from below with a blackened 58-cm diameter plywood disk to reduce surface reflection. The top of the sensor was about 12 cm above the disk, resulting in an angle of about 1.96 radians (112°) from the vertical to a line from the top of the sensor to the edge of the disk. Consequently, about 2.8π steradians of exposure occurred at the top of the in-air sensor. Two underwater sensors were floated at known fixed depths below the water surface.

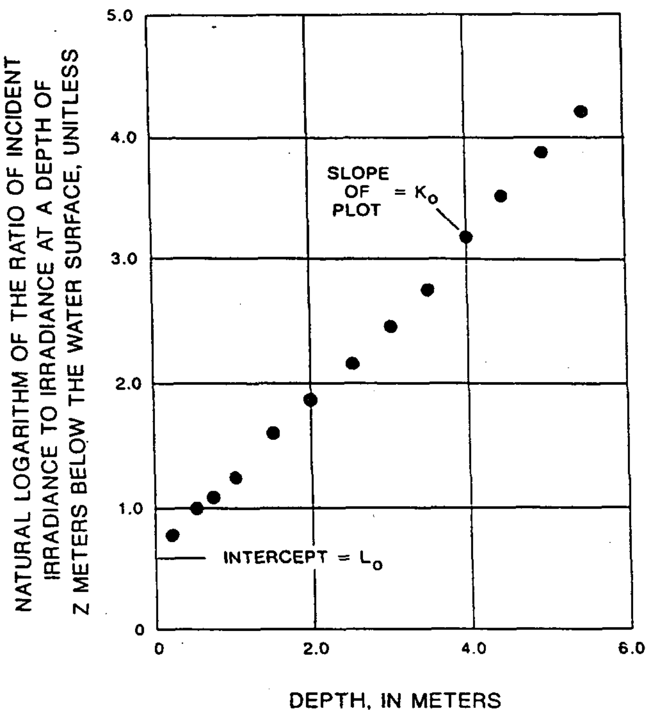
Irradiance data from the underwater and in-air sensors were used to compute k_0, the vertical attenuation coefficient for scalar irradiance, and L_0, the intercept of the following modified form of the Bouger-Lambert law.

$$\ln(E_I/E_z) = k_0 \cdot z + L_0, \qquad (1)$$

where E_I is the incident (in-air) irradiance, E_z is the irradiance at a depth of z meters in water, k_0 is the slope of the relation between $\ln(E_I/E_z)$ and depth (z) (Figure 2), and L_0 is the intercept of the regression line drawn through the data in Figure 2 and is related to the apparent loss of PAR at the air-water interface. L_0 and k_0 were computed from the continuous averages of PAR measured in air and at two depths in water and used to calibrate the model equations. Irradiance for the shallow (E_z) and the in-air (E_I) sensors and the depth (z) of the shallow sensor were substituted into equation 1, leaving L_0 and k_0 as unknowns. Similarly, the data for the deep sensor were substituted into equation 1; this gives two equations in two unknowns that were solved for L_0 and k_0.

Although equation 1 is strictly linear only for monochromatic radiation, curvature in plots of $\ln(E_I/E_z)$ as a function of z is generally small enough that it can be used to determine k_0 in a wide range of natural waters (McPherson and Miller, 1987).

Figure 2. Relation between the natural logarithm of the ratio of the incident PAR irradiance (E_I) to the irradiance (E_z) at a depth z meters in water and the depth (z).



At a depth of 0 in water, equation 1 reduces to

$$\ln(E_I/E_0) = L_0, \tag{2}$$

where E_0 is the irradiance in water extrapolated to a depth of 0 m (just below the air-water interface). The fraction of incident PAR irradiance just below the water surface, f_r, was computed from field data using

$$f_r = E_0/E_I = \exp(-L_0), \tag{3}$$

The average zenith angle (Θ) of the refracted direct solar beam in water was computed from the solar elevation angle (β) by using Snell's law and the assumption that the effects of wave action averages to the refracted angle of a calm sea surface by

$$\Theta = \arcsin(\sin(90° - \beta)/1.33) \tag{4}$$

MODEL DEVELOPMENT AND CALIBRATION

A simple model for the behavior of f_r was assumed as

$$f_r = f_{diff}\cdot(1-D) + f_{dir}\cdot D, \tag{5}$$

where f_{diff} is the fraction of diffuse skylight in air that enters the water, D is the fraction of light in air that is direct solar beam, and f_{dir} is the fraction of direct solar beam light that enters the water. Because a direct measure of D is unavailable, E_I/E_{max}, the ratio of the measured irradiance in air (E_I) to the maximum amount of irradiance in air (E_{max}) computed for the same solar elevation angle on a very clear day, is substituted to model f_r by

$$f_r = b_0 - b_1 \cdot(E_I/E_{max}) + b_2\cdot\sin(\beta)\cdot(E_I/E_{max}), \tag{6}$$

where b_0. b_1, and b_2 are regression coefficients. E_{max} was estimated by grouping 16,880 observations of incident PAR to the nearest degree (±0.5°) of solar elevation angle and averaging the highest five values within each group. The PAR averages are used to develop a cubic polynomial that describes the upper boundary of the averages as a function of solar elevation angles on very clear days in the Tampa Bay area.

The approximate separation of light into diffuse and direct solar beam components in equation 6 also was used to model the average angle and length of the light path in water. The cosine of the average zenith angle of the refracted diffuse irradiance, μ_{diff}, and of the refracted direct solar beam, cos(Θ), weighted using the fractions of refracted PAR predicted in equation 6, were used to compute a weighted average cosine, μ_{wtd}, for all refracted PAR using the equation

$$\mu_{wtd} = \frac{\mu_{diff} \cdot (b_0 - b_1 \cdot (E_I/E_{max})) + \cos(\Theta) \cdot b_2 \cdot \sin(\beta) \cdot (E_I/E_{max})}{b_0 - b_1 \cdot (E_I/E_{max}) + b_2 \cdot \sin(\beta) \cdot (E_I/E_{max})} \quad (7)$$

The value of μ_{diff} probably varies some as cloud conditions change, but was treated as a constant in the model. The μ_{wtd} is similar to the μ_0 presented by Kirk (1984), where μ_0 is the cosine of the angle of the direct solar beam just below the air-water interface. However, μ_{wtd} also incorporates diffuse skylight. The μ_{wtd} is used to compute k_{adj}, the adjusted attenuation coefficient for scalar irradiance, from k_0 using the equation

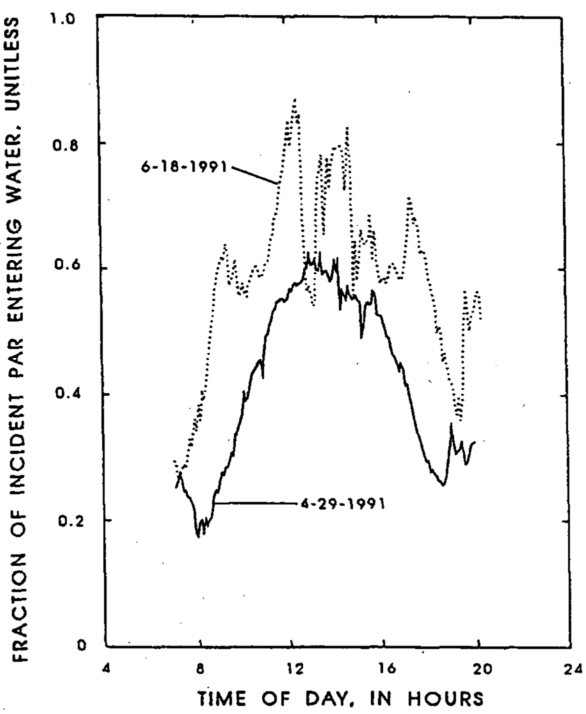
$$k_{adj} = \mu_{wtd} \cdot k_0, \quad (8)$$

RESULTS AND DISCUSSION

The fraction of direct solar beam and diffuse skylight that entered the water varied with changes in cloud cover (modeled as E_I/E_{max}) and solar elevation angle. For example, under partly cloudy skies on June 18, 1991, the observed fraction that entered the water increased from 27 percent in early morning to 87 percent when the sun broke through the clouds near solar noon (Figure 3). Most of the incident light on

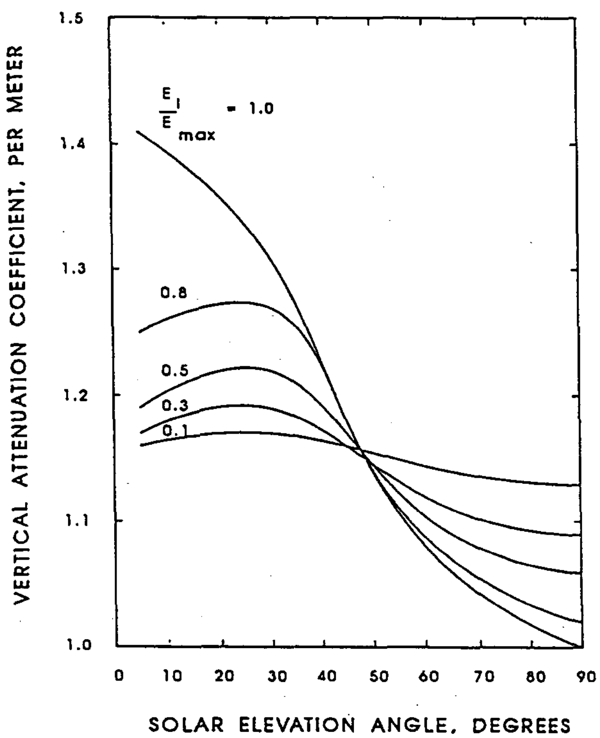
April 29, 1991, was direct solar beam, and the fraction that entered the water varied between 17 and 62 percent as cloudiness and solar angle changed. Before sunrise, up to 27 percent of the diffuse skylight entered the water. Shortly after sunrise, incident irradiance increased, but the fraction entering the water decreased (Figure 3) because the relative density of direct solar beam photons per unit area of water surface was low. The general shape of the April 29 plot of f_r in Figure 3 is typical for relatively clear days; the minima for f_r occur at low solar elevation angles near sunrise and sunset and the maximum occurs near solar noon. Cloudiness reduces the difference between the daily maxima and the minimum by reducing the fraction of incident PAR that is direct solar beam and, consequently, the influence of angular effects of the direct solar beam on f_r. The daily and seasonal variations in solar elevation angle and in the fraction of diffuse skylight and direct solar beam that enters the water determine the average angle of PAR entering the water. The angle that PAR enters the water

Figure 3. Observed fraction of incident PAR that entered the water.



determines the average length of the light path in water and, consequently, the value of k_0. For the Tampa Bay area, the midmonth solar elevation angles at solar noon are 40.8, 49.1, 58.8, 71.9, 81.0, 85.4, 83.7, 76.1, 65.1, 53.6, 43.6, and 38.9° in January through December, respectively. The midmonthsolar elevation angles at solar noon and the model results shown in Figure 4 can be used together to estimate the magnitude of daily and seasonal variations in k_0. The model results indicate that on clear days, k_0 in Tampa Bay will be about 41 percent greater than k_{adj} near sunrise and that this difference will decrease to about 23 percent of k_{adj} at mid-day in December and to near 0 percent at mid-day in June. On cloudy days, much of the incident light is diffuse and k_0 tends to be about 10 to 20 percent greater than k_{adj} throughout the day (Figure 4). The approach demonstrated in Figure 4 makes it possible to reduce some solar

Figure 4. Modeled values of the vertical attenuation coefficient for scalar irradiance (k_0) over a range of solar elevation angles and at selected ratios (E_I/E_{max}) of incident PAR irradiance to the maximum PAR irradiance predicted at the same solar elevation angle for very clear skies. The predicted attenuation coefficients (k_0) are for a 'true' attenuation coefficient (k_{adj}) of 1.00 m^{-1}.



angle and cloud-related effects on k_0 by adjusting it to k_{adj} (eq. 8). Values of k_{adj} will better correlate with water-quality constituents that cause attenuation than the uncorrected k_0. The original k_0 data, however, need to be archived with date, time, adjustment to Greenwich Mean Time, solar elevation angle, and incident light because methods for adjusting k_0 for the effects of solar elevation angle and cloudiness may improve. Direct measurement of the fractions of incident PAR that is diffuse skylight and direct solar beam should improve the capability for modeling and correcting for the effects of solar elevation angle and cloudiness on f_r and k_0.

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CAUSES OF LIGHT ATTENUATION IN ESTUARINE WATERS OF SOUTHWESTERN FLORIDA

by

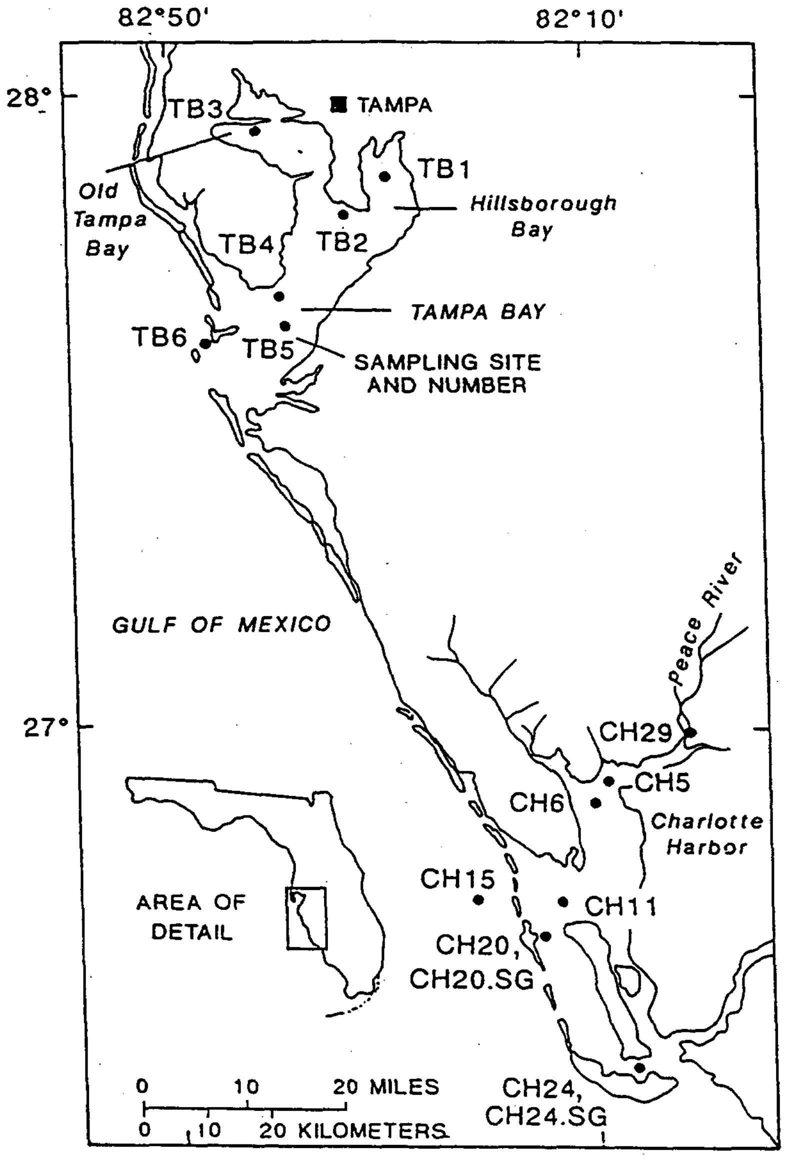
Benjamin F. McPherson
and
Ronald L. Miller
U.S. Geological Survey,
4710 Eisenhower Blvd., Suite B-5,
Tampa, FL 33634, U.S.A.

INTRODUCTION

The distribution and availability of photosynthetically active radiation (PAR) in estuarine waters were evaluated by measuring irradiance at different depths to determine the vertical diffuse attenuation coefficient, k_0, The attenuation coefficient, k_0, is an apparent optical property and is affected by the ambient light field, including solar angle, cloud cover, and water depth, in addition to dissolved and suspended constituents in the water (Gallegos and Correll, 1990). This study evaluates the relative importance of solar angle and water-quality constituents on light attenuation in Tampa Bay and Charlotte Harbor, Florida (Figure 1), and predicts how attenuation might change under different water-quality conditions. Support for this study was provided by the U.S. Geological Survey and the Southwest Florida Water Management District through a jointly funded investigation. A comprehensive paper that describes the investigation has been submitted for publication. The following results are extracted from the comprehensive paper.

In this study, we used a simple formula to partially adjust the attenuation coefficient for changes in solar angle by assuming that much of the downwelling light in water follows the path of the refracted direct solar beam. We used multiple regression techniques to derive partial attenuation coefficients for constituents in the water and used these coefficients to partition attenuation.

Figure 1. Locations of Tampa Bay and Charlotte Harbor, Florida, and sampling sites.



METHODS AND APPROACH

We established 15 stations in Tampa Bay and Charlotte Harbor and sampled every 1 to 2 months from October 1989 to October 1991. PAR, in microeinsteins per square meter per second [$\mu E\ (m^2 s)^{-1}$], was measured using a spherical quantum sensor (LICOR LI-193SA)[a]. Simultaneous measurements of PAR were made in the air and in the water using a LICOR 1000 data logger with two spherical quantum sensors. The "in-air" sensor was mounted above a 0.6-m diameter circular black disk on a 2-m pole, and the "in-water" sensor was lowered through the water column to a series of measurement depths, usually to 2.5 m or to a position near the bottom. Average (10-second) measurements of scalar irradiance were made at each measurement depth. The in-air irradiance was used to adjust the in-water irradiance for changes in the incident irradiance during the series of underwater measurements. The natural logarithm of the ratio of simultaneous in-air to in-water PAR values was plotted against depth, and a least squares fit of the data was used to obtain k_0 the slope. Four replicate vertical profiles were made at each station. Attenuation coefficients also were calculated at 5-minute intervals at one site on 22 days in 1990-91. For the measurements at this site, two spherical quantum sensors were floated at fixed depths below the water surface, separated by an interval of either 1 or 2 m, and irradiance at these two depths was simultaneously recorded every 5 minutes and used to compute an attenuation coefficient. In-air irradiance also was measured.

Depth-integrated water samples were collected from the surface to the deepest PAR measurement depth for analysis of color, turbidity, specific conductance, nutrients, and chlorophyll *a*. These samples were chilled to about 4 ^{0}C and shipped to the laboratory for analysis using methods listed by Fishman and Friedman (1989) and Greeson and others (1977). Color, in platinum-cobalt units (Pt-Co units), was measured by color comparator. Turbidity was measured by comparing the light scattered by the sample with that scattered by a standard reference suspension. Specific conductance was determined from electrical resistance and used to estimate salinity in parts per thousand (ppt). Nutrient concentrations were determined using colorimetric methods. Chlorophyll-*a* samples were filtered onto glass-fiber filters in the field and transported to the laboratory on ice and held at 4 °C in the dark until analyzed (within 2 weeks of

[a] Use of brand names in this article is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

collection). Concentrations of chlorophyll *a* were measured by high performance liquid chromatography using a fluorometric detector. We used a modified form of the Bouger-Lambert law to determine the attenuation coefficient, k_0 and then adjusted the coefficient using a simple model described by Kirk (1991) to partially account for the longer light path of the refracted direct solar beam in water using the following equation:

$$k_{adj} = k_0 \cdot \mu_0 \qquad (1)$$

where k_{adj} equals the adjusted attenuation coefficient and μ_0 equals the cosine of the zenith angle of the refracted direct solar beam. The coefficient k_{adj} was then partitioned into partial attenuation coefficients as follows:

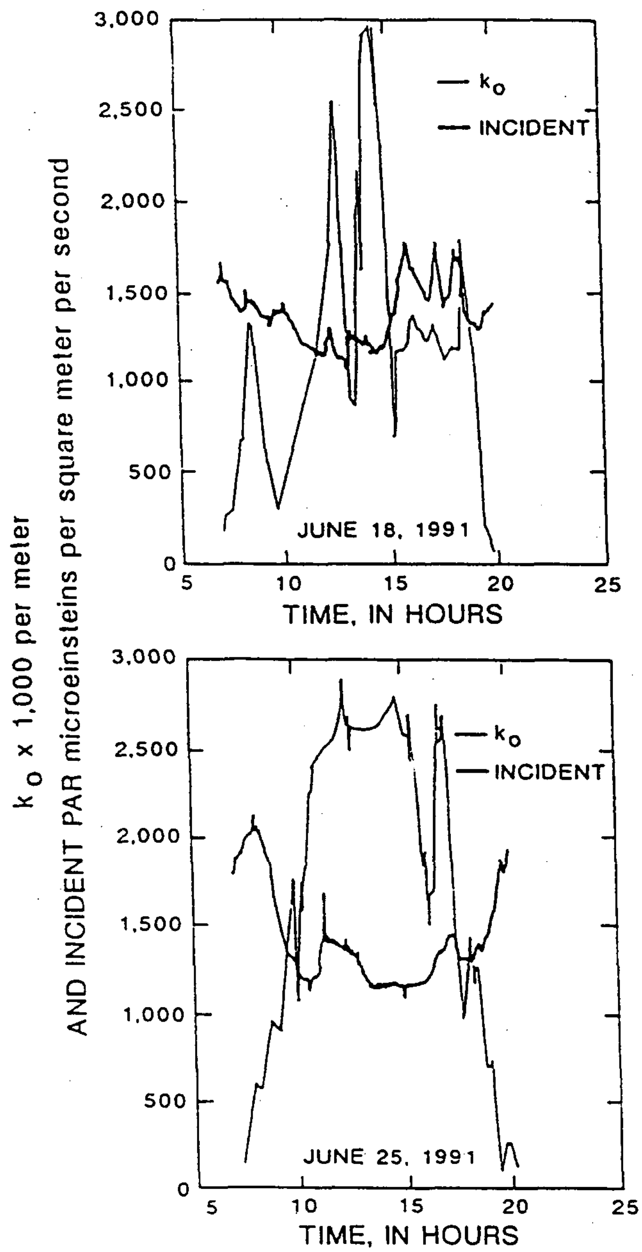
$$k_{adj} = k_w + E_2 \cdot C_2 + E_3 \cdot C_3 + E_4 \cdot C_4 \qquad (2)$$

where k_w is the attenuation coefficient of seawater, 0.0384 m^{-1} (Lorenzen, 1972); E_2 is the attenuation coefficient of dissolved matter, in (m Pt-Co units)$^{-1}$; C_2 is water color, in Pt-Co units; E_3 is the attenuation coefficient of chlorophyll and other matter associated with chlorophyll *a* by regression analysis, in m^2 mg^{-1}; C_3 is the concentration of chlorophyll *a* in mg m^{-3}; E_4 is the attenuation coefficient of nonchlorophyll suspended matter (NSM), which includes inorganic and organic particulates not directly associated with color or chlorophyll *a* in m^2 mg^{-1}; and C_4 is the concentration of NSM, in mg m^{-3}. The partial attenuation coefficients for color and chlorophyll *a* in equation 2 were derived by stepwise multiple regression analysis and were multiplied by concentrations to yield the contribution of each to attenuation. The contribution of NSM was estimated by subtraction (k_{adj} - k_w - E_2C_2 - E_3C_3). The contribution of each property or constituent was expressed as a percent of k_{adj}.

RESULTS

Light attenuation varied significantly during some days as a result of changes in solar angle. For the 22 days with measurements at 5-minute increments at a site in Old Tampa Bay (TB3), k_0 declined during midday on 18 days. The curves of k_0 plotted

Figure 2. In-air incident PAR and the attneuation coefficient k_0 (multiplied by 1,000) on a mostly cloudy day (June 18, 1991) and a mostly clear day (June 25, 1991) at site TB3 in Old Tampa Bay.



against time of day were often U-shaped, although this pattern was more evident on clear than on cloudy days (Figure 2). Light attenuation and water quality varied spatially throughout Tampa Bay and Charlotte Harbor. Most values of the adjusted attenuation coefficient, k_{adj}, were less than 1.0 m^{-1} and k_{adj} increased with decreasing salinity and increasing color. Highest values of k_{adj} (greater than 3.0 m^{-1}) occurred in northern Charlotte Harbor and in the tidal Peace River where highly colored (greater than 100 Pt-Co units) freshwater flowed into the estuary. Concentrations of chlorophyll *a* were highest and most variable in the salinity range from 10 to 30 ppt, and concentrations were relatively low at both high and low salinities.

The partial attenuation coefficient for color and chlorophyll *a* are given in the following regression equation ($r^2 = 0.83$, $p<0.000$).

$$k_{adj} = 0.014 \cdot C_2 + 0.058 \cdot C_3 + 0.42 \qquad (3)$$

The partial attenuation coefficient for chlorophyll *a* in equation 3 is higher than that reported by others (Kirk, 1983), probably because of differences in methods used for chlorophyll-*a* analyses. Our concentrations of chlorophyll *a* were determined by separating pigments with high performance liquid chromatography and measuring concentrations with a fluorometric detector. Methods that separate pigments prior to determination of chlorophyll *a* can yield low concentration values compared with other methods. The coefficients in equation 3 were used to compute changes in k_{adj} and depth to 10 percent of incident light that would occur with changes in concentrations of either color or chlorophyll *a*, assuming other concentrations in equation 2 remained constant at average values (Figure 3). The coefficients were also used to compute the percent of contribution for each constituent in equation 2 to k_{adj} (Table 1).

Nonchlorophyll suspended matter (NSM) was the dominant cause of attenuation in Tampa Bay and Charlotte Harbor and was responsible on average for about 55 percent of k_{adj} (Table 1). Chlorophyll *a* and color were responsible on average for 21 and 18 percent of k_{adj}, respectively, and seawater was responsible for the remaining 6 percent. Chlorophyll *a* contributed 27 percent to k_{adj} in Tampa Bay compared with 16 percent in Charlotte Harbor. Color contributed 13 percent to k_{adj} in Tampa Bay compared with 22 percent in Charlotte Harbor. Color was the primary cause of light attenuation in northern (upper) Charlotte Harbor and in the tidal Peace River (Table 1).

Figure 3. Changes in the adjusted attenuation coefficient, k_{adj}, and depth to 10 percent of incident light projected using equation 3 for (A) changes in the concentration of chlorophyll *a*, assuming an average value of color (13 Pt-Co units) and (B) changes in color, assuming an average concentration of chlorophyll *a* (2.8 µg L^{-1}).

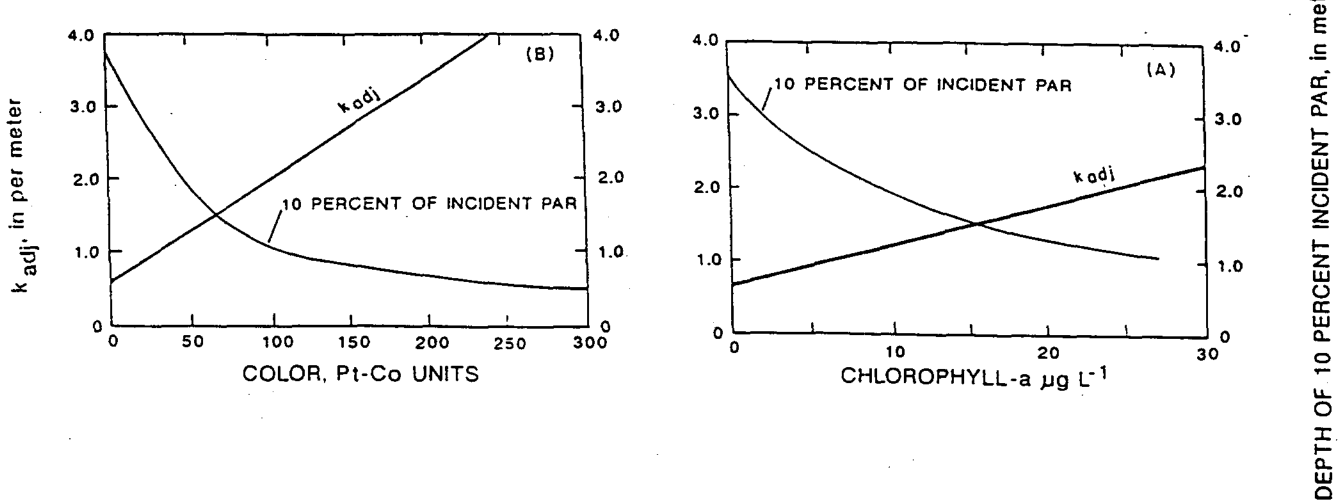


Table 1. Average percent contribution of water characteristics to total light attenuation in Tampa Bay (TB) and Charlotte Harbor (CH) [Parenthesis contain the range in percent. N is the number of samples]

Water characteristics	All data	Tampa Bay	Charlotte Harbor	Upper Tampa Bay	Upper Charlotte Harbor[1]
	N=207	N=82	N=117	N=36	N=21
Color	18 (3-93)	13 (3-53)	22 (4-93)	12 (3-53)	49 (5-93)
Chlorophyll *a*	21 (0-97)	27 (5-97)	16 (0-43)	28 (5-84)	18 (0-43)
Nonchlorophyll suspended matter	55 (0-86)	54 (0-86)	55 (0-82)	56 (0-86)	30 (0-70)
Seawater	6 (1-19)	6 (2-13)	7 (1-19)	4 (2-9)	3 (1-7)

[1]Includes a site in the tidal Peace River.

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PAR SECTION 3:

SUMMARY AND CONCLUSIONS

PAR/SAV Workshop Summary and Conclusions

by

Lori J. Morris
and
Robert W. Virnstein
St. Johns River Water Management District
P.O. Box 1429
Palatka, FL 32178

The goals for the workshop were to answer the following questions and to develop a protocol for measuring light in the aquatic environment:

* **What should be measured?**
* **What is the correct sensor to use to measure the available light?**
* **What methodology for measuring light can answer questions of:**
    * **Correction for cloud cover?**
    * **Stratified water column?**
    * **Consistent depth profile?**
    * **Correction for sun angle?**
    * **Appropriate time-of-day?**
    * **Required replication?**
* **How frequently should light be measured?**
* **What is the best way to calculate attenuation (K)?**
* **How should PAR or K be used as a management tool?**

DISCUSSION

What should be measured? Is downwelling attenuation the main factor, or are the optical properties of the water column more important to measure?

In order to achieve the SWIM goal of attaining and maintaining a functioning macrophyte-based ecosystem in the Indian River Lagoon, priority must first be placed on **improving water clarity**.

The vertical attenuation coefficient (K) is a value used as an indicator of water clarity, but it does not determine the causes of attenuation. To understand what is causing the attenuation, other parameters need to be measured along with PAR. These parameters directly affect water clarity. They include measurements of particulate matter (total suspended solids, TSS; mineral suspended solids, MSS; particulate organic matter, POC; and total organic matter, TOC); color; chlorophyll; and light. Other water quality factors affect water clarity only indirectly, e.g. by controlling the growth of phytoplankton and epiphytic algae. These factors include the total organic and inorganic nutrient concentrations.

Which sensor, a 2π or 4π, is the most appropriate one to use? The structural and functional differences between the two sensors are listed below. The main issue of the relative merits between the two sensor types was based on the goals of the sampling and the factors to be measured.

2π -- Also known as a cosine-corrected sensor. The 2π sensor measures downwelling irradiance (90° either side of vertical) only, avoiding any bottom reflectance. Therefore, if the goal is to measure downwelling light attenuation a 2π sensor should be used. However, a 2π sensor may seriously underestimate the amount of light available for photosynthesis.

4π -- Also known as a spherical sensor. The 4π sensor measures scalar irradiance (360°), including both bottom reflectance and scattered light. The use of a 4π sensors has been primarily for phytoplankton studies in the past. It has been stated that "serious problems may be encountered when using a spherical sensor in shallow estuarine waters." Because of their variable physical orientation, blades capture light from every angle. Therefore, the sensor should also be able to measure the available light from all angles, and a 4π sensor is designed to do this.

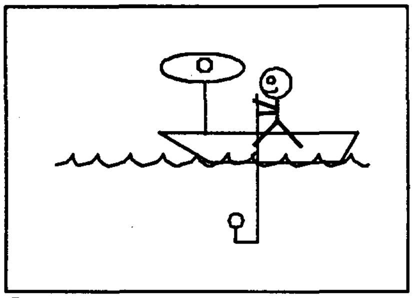
Therefore, based on the reasoning above, a decision was made to **use the spherical, 4π sensors** for monitoring the light available to the seagrasses.

HOW to measure PAR? Several examples of "stickmen" were presented using different configurations of sensors. Stickmen #1 and #2 are methods used by the majority of agencies measuring PAR in the Lagoon already. The main difference between the two is that Stickman #1 uses an in-air reference sensor and Stickman #2 uses a submerged one. Stickman #3 allows the submerged sensor to slide up and down a pole fixed on the bottom. This set-up can use either an in-air or submerged reference sensor. Stickman #4 does not use a reference sensor but uses two submerged sensors fixed a set distance apart (ΔD). Each configuration has its pros and cons, but one, or a combination of them, needs to be adopted for consistency and comparisons (Figure 1). However, Stickman #2 was chosen as the most appropriate configuration to start with (see SUMMARY below)

What is an appropriate depth profile to use for a stratified water column? Preliminary work from Taylor Creek, opposite Ft. Pierce Inlet, has shown that when sampling in a stratified water column, it is important to take water-column integrated samples, both for light and water quality. Light readings taken through a stratified water column will show a larger attenuation in the surface layers compared to the deeper layers. Therefore, in order to adequately sample the number of areas throughout the Lagoon where the water column is stratified, an agreement was made to **sample every 20 cm to 100 cm (20, 40, 60, 80, 100 cm) and then again near the bottom.**

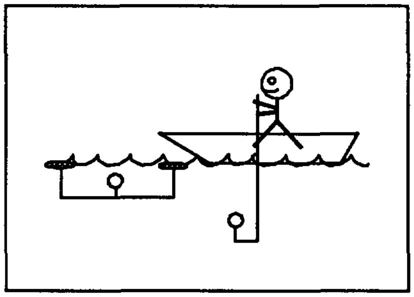
How can corrections for sun angle be made? Angle-of-the-sun corrections can be made by applying an algorithm developed by Ron Miller and Ben McPherson (see papers in these proceedings). Without correcting for sun angle, a 10-20% error can be introduced. This error can easily be avoided by using an **in-air deck sensor for the sun angle correction.**

Figure 1.



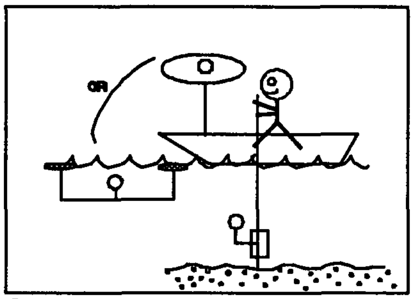
Stickman #1

	PROS	CONS
Stickman #1	Easily handled by one person.	Difficult to correct submerged sensor for cloud cover.



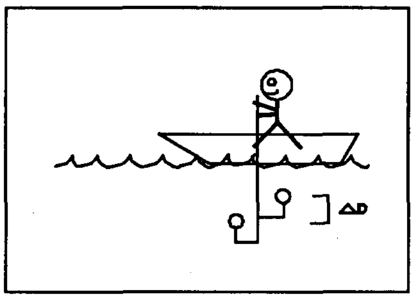
Stickman #2

	PROS	CONS
Stickman #2	Stationary submerged reference sensor allows direct correction for cloud cover.	



Stickman #3

	PROS	CONS
Stickman #3	Knowing exact depth of the sensor with relation to the bottom.	If boat is moving too much it will be difficult to hold the sensor steady.



Stickman #4

	PROS	CONS
Stickman #4	Knowing fixed ΔD between the sensors at all times.	No correction for cloud or time of day. Unable to calculate K_d for integrated water column.

Appropriate time of day to sample? The "sampling window" of 10:00 am to 2:00 pm will still hold until corrections are available for measurements outside this window. It was decided that further analysis of the data needs to be made before this window could be enlarged. We need to be more confident with the corrections for this, especially during the winter months.

Sampling frequency; how often and where should sampling occur? Temporal and spatial variability are very difficult to determine without a long-term data set. The best guideline to follow is the "half rule." The half rule states that once the distance is determined where change can no longer be detected, that distance is divided in half and a sample is taken. For example, if no change is detected in 10 km, then samples are taken every 5 km, or if there is no change over a 1-hour period then samples are taken every half hour.

However, the half rule will only work when you know the frequency of variability, and that can only be determined from data collected over a long time period. This type of long-term, site-specific research is now being implemented for the Lagoon in order for these kinds of questions to be answered. Until then, it was decided that each agency continue with its same sampling schedule.

How is attenuation, or K_d, most accurately calculated? Attenuation coefficients were calculated using two different formulas, semi-log regression with depth and a calculation treating each depth interval as a total water column. The two calculated K values were correlated with each other. The regression showed a surprisingly large amount of scatter around the 1:1 trend line. Most importantly, this scatter demonstrated that there are no easy short-cuts for calculating attenuation. **The most efficient, reliable method is to log transform the PAR data and regress it over the depth profile to produce a semi-log regression.**

SUMMARY

From all the discussions of the above questions a new protocol was developed for the Water Quality/PAR Monitoring Network in the Indian River Lagoon.

* **WHAT are we trying to measure ?**
  WATER CLARITY is the most important factor to measure.

* **WHICH is the correct sensor to use ?**
  A 4π sensor is the most appropriate sensor to use in order to measure the total available light.

* **WHAT is the proper set-up to use for measuring PAR?**
  The new protocol will be in accordance with PAR man.

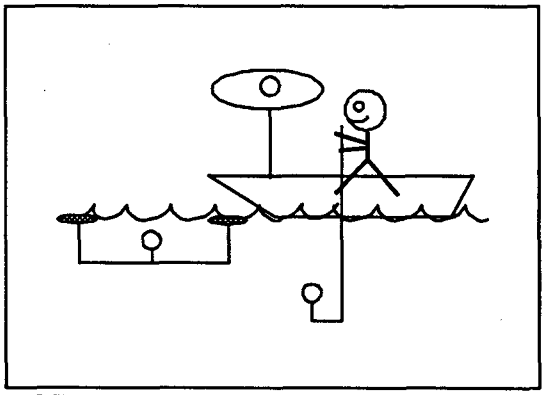
★ Using three 4π sensors: in-air deck sensor, 15 cm submerged reference sensor, and one lowered through the water column.

★ Sampling should be during a 10:00 am to 2:00 pm window.

★ Depth profile of 20, 40, 60, 80, 100 cm and near bottom.

★ A minimum of 10-second integration time at each depth.

★ Replicating each profile a minimum of three times.



PAR MAN

* **HOW often to we need to sample?**
  Until ongoing research is completed, each agency will continue with its present sampling schedule.

* **WHAT is the best way to calculate attenuation, K?**
  Use a semi-log regression of the irradiance values measured along the depth profile.

* **HOW can we use PAR or K values as a management tool?**
  Partitioning the sources or causes for increased attenuation will enable water clarity to be related back to water quality parameters. This relationship will ultimately allow the light requirements for SAV to be translated into water quality requirements. These requirements will in turn enable goals and targets (PLRGS -- Pollution Load Reduction Goals) to be established for improving and maintaining the resource. The goal is to develop a predictive simulation model to substantiate future improvements.

APPENDIX I

APPENDIX I

SUBMERGED AQUATIC VEGETATION INITIATIVE

The mission of the Indian River Lagoon National Estuary Program is to coordinate the efforts of the federal, state and local governments to protect and restore the Indian River Lagoon, an estuary of national significance.

ISSUE

Submerged Aquatic Vegetation (SAV) is a critical component of the Indian River Lagoon ecosystem, playing an important role in biological productivity and species diversity. Since the 1950's, however, the areal extent of SAV within the lagoon has been dramatically reduced. Estimated losses of SAV have reached 100% in areas of the Lagoon (DNR, 1985).

This decline in SAV coverage has been largely attributed to adverse water quality conditions, particularly the reduction in water clarity. The reduction in water clarity has resulted in reduced SAV, which in turn affects the viability of the SAV community.

GOAL

The goal of the SAV Initiative is to increase the amount and quality of seagrass and associated resources in the Indian River Lagoon.

In a more technical sense the goal of the SAV Initiative is to develop and use management techniques for the purpose of increasing the amount and quality of seagrass and seagrass resources in the Indian River Lagoon. This will be accomplished by developing resource-based water quality standards which may guide the management of surface water runoff as well as other practices designed to improve overall water clarity by reducing total suspended solids and nutrients entering the lagoon. The SAV Initiative pulls together several elements of the

IRLNEP program and provides an immediate impetus for the testing of watershed and other management projects intended to reduce the loading of suspended solids and nutrients to the lagoon or otherwise improve water quality to benefit seagrasses.

BACKGROUND

Initial efforts by the scientific community to summarize concerns about the Indian River Lagoon culminated in 1981 with the Future of the Indian River Lagoon Conference. At this meeting the participants exchanged information and opinions regarding the observed decline of the lagoon. The results were published in the journal, "Florida Scientist".

Partially as a result of FIRST, the Marine Resources Council of East Florida (MRC) was formed in 1983. In 1985 the MRC, with members of the scientific community, organized the Indian River Resource Symposium. This two day event, consisting of technical presentations and American Assembly sessions, culminated in a general consensus on the most important issues related to the lagoon's vitality. Among the three primary issues identified at that time was [the] "limited understanding of the relationship of the physical processes to the biological system, particularly the submerged aquatic vegetation, the basis of life in the lagoon."

Based on the symposium results, the Governor established the Indian River Lagoon Field Committee (IRLFC) with representatives from the state, regional and local agencies, water management districts, members of the scientific community, and citizens. The IRLFC met for approximately 18 months between June 1985 and January 1987 to consider marine resources, water management and growth management issues and to develop a management plan for the lagoon system.

Within this plan several policies were developed relative to seagrasses. These include policies relating to monitoring and the management of surface water runoff. These policies are pertinent to the Submerged Aquatic Vegetation Initiative and the mission of the Indian River Lagoon National Estuary Program.

These policies include:

1.31 Seagrass and submerged aquatic vegetation research shall be initiated and funded to investigate the relationship between water quality (i.e. turbidity, light penetration, nutrients, etc.) growth, stress on seagrasses, and organism relationships.

3.61 Reexamine the scientific basis for the Department of Environmental Regulation N.T.U. turbidity standards. Turbidity standards should be sufficiently stringent to protect aquatic life from harm by siltation and light deprivation under a range of naturally occurring and site specific "background" turbidity levels.

2.21 Authorize and fund a comprehensive ecological monitoring and research program, including but not limited to water, sediment, and biological quality.

4.42 Establish improved water quality monitoring networks.

3.31 Establish performance standards and Best Management Practices for direct surface runoff to the lagoon.

3.62 Establish a stricter turbidity standard and control measures for dredging and filling and related operations in Class II waters and in the vicinity of attached submerged aquatic vegetation.

Partially as a result of the IRLFC recommendations, the Legislature passed the Surface Water Improvement and Management (SWIM) Act and provided limited funding for the initial implementation of the SWIM program through the water management districts.

Through the SWIM program, the St. Johns River Water Management District (SJRWMD) has developed a management plan for the Indian River Lagoon which addresses three major issue categories of water and sediment quality, habitat alteration/loss and inter-agency management. A primary goal of the SWIM plan is "to attain and maintain water and sediment of sufficient quality to support a healthy, macrophyte-based, estuarine lagoon system."

Due in part to the initiative created by the Marine Resources Council and through the SWIM program, the Indian River Lagoon was nominated by the Governor as an estuary of national significance. This nomination was recognized and an Indian River Lagoon Management Conference convened in 1990 with the Conference Agreement initiating the Indian River Lagoon National Estuary Program during April 1991. Building upon previous efforts, the IRLNEP largely adopted the goals of the SWIM program including those related to water and sediment quality.

An initial list of priority problems developed through the IRLNEP include:

-Loss of seagrass beds and increased stress on remaining beds.
-Increased nutrient loadings.
-Increased suspended matter loadings and sedimentation.

During the fall of 1991 the Coastal Lagoons Assembly was held as a cooperative venture of the IRLNEP and the MRC. Included in the consensus summary of this event were the long-term goals of establishing a centralized water quality study for habitat protection purposes and for developing baseline data on seagrasses, including the continual updating of seagrass maps for use by the local governments in land-use decision making.

RATIONALE FOR SAVI

The need for a resource based standard for the Indian River Lagoon (IRL) has grown out of the recognition that present state and federal standards, developed for application state and nationwide, are inadequate to protect the resources of the IRL. although the IRL generally meets or exceeds state and federal water quality standards, declines have been documented in the extent and quality of the SAV community.

From this review of the events preceding the development of the SAV Initiative, it is clear that the development of a resource based water quality standard is needed. Such a standard could be used to guide land-use and other management strategy decisions affecting the lagoon, which has been contemplated and recommended for some time.

SAVI GOAL AND BENEFITS

The goal of the Submerged Aquatic Vegetation Initiative is to increase the amount and quality of seagrass and associated resources in the Indian River Lagoon.

The specific benefits of resource based water quality standards are many and include considerations such as:

A clear connection between project goals and desired outcome, i.e. the direct relations between improved water clarity and the improvement of seagrass habitat is easily demonstrated and understood.
An early determination of specific, and relatively limited, parameters (suspended solids, nutrients and color) provides parameters for testing the effectiveness of demonstration projects which may be undertaken while SAV research is occurring.

Physical products such as resource maps will be provided which graphically illustrate the effectiveness of management activities and which clearly depict the goal of the SAV Initiative.

The information provided (water quality targets) from the initiative is "localized" by the lagoon segment which makes these standards especially meaningful to the local governments concerned with watershed management within those segments.

The information is easily interpreted and is meaningful to local citizens which will be asked to fund management activities through MSTU, MSBU, stormwater utilities and other funding means.

General benefits include:

enhanced recreational use to improved water clarity and enhanced fisheries yield.

enhanced food source and habitat for endangered and threatened species.

maintenance or improvement of current water body classification which provides maintenance of the shell-fishing industry.

MANAGEMENT CONFERENCE COMMITMENT

The SAVI relates either directly or indirectly to five of the six commitments of the IRLNEP management conference.

Assess trends in water quality, natural resources and the uses of the lagoon.

Provide for monitoring to assess the effectiveness of implemented actions.

The SAVI would initiate a modified sampling program from that currently in effect. The SAVI program would target specific sampling parameters (TSS, chlorophyll, color) for the purpose of monitoring and assessing the effectiveness of management activities relative to qualities associated with improved seagrass growing conditions.

The IRLNEP Characterization Report will provide analysis of water quality trends based upon historical data. The SAVI calls for increased coordination among water quality sampling programs.

Determine causes of change through data collection, characterization and analysis.

Evaluate point and non-point loadings and relate these to observed changes.

An important component of the SAVI is determining specific impacts for human activities and other pollution sources as well as characterizing the system in a manner in which segmentation for the SAVI will be most effective. The IRLNEP Characterization Report, an important component of the SAVI, will provide insight to causes of change and target pollution "hot spots" which will be needed for the development of resource based water quality standards and will be important to the development of an effective segmentation plan under the SAVI.

Develop a CCMP which recommends priority actions and delineates plans to coordinate implementation and recommended actions.

The purpose of the SAVI (i.e. sediment controls, and nutrient loading reductions) which are meaningful to the restoration of the Indian River Lagoon. In concert with the SAVI, the testing (through demonstration projects) of management strategies or through technical support of local restoration initiatives will provide specific recommendations of inclusion in the CCMP.

SAVI OBJECTIVES, STRATEGIES AND PROJECTS

OBJECTIVES

- Preservation, enhancement, and restoration of the SAV community in the Indian River Lagoon by attaining and maintaining an environmental condition throughout the Indian River Lagoon capable of supporting a healthy SAV community to a depth of two meters. (This objective may be accomplished by a tiered approach.)

- Coordination and definition of the roles and funding resources of the agencies and institutions involved in management, regulation, and research of the SAV community.

- Development and implementation of resource (SAV) based water quality targets for SAV for the Indian River Lagoon.

- Utilization of resource (SAV) based water quality targets in the development and implementation of watershed management practices.

- Monitoring of SAV communities for functionality, reporting on the effectiveness and progress of watershed management practices in meeting the overall SAV goal.

STRATEGIES

- Continued lagoon-wide SAV mapping efforts on a regular basis to detect spatial and temporal trends in SAV coverage.

- Develop adequate lagoon-wide bathymetric information to accurately define areas of potential SAV coverage. If a bathymetric study for the entire lagoon is not feasible, bathymetry could be done at transect sites, areas ground-truthed during SAV mapping or selected areas.

- Modify existing or developing a new water quality and PAR monitoring network tailored to the needs of individual lagoon segments. Additional information on PAR is needed. Possible minimum sampling intervals 5-10 days or weekly. Monitoring biota in SAV beds to insure that these areas are functioning in a typical manner.

- Establish long-term research/reference areas to study SAV community dynamics, function, water and sediment quality, etc. It is recommended that four sites be established.

- It is important to map SAV frequently, preferably on a one to two year return.

- If it is not possible to undertake a full mapping project, at the minimum aerial photography should be obtained for future reference and interpretation.

- Transects are an important means of monitoring the health, composition, and status of the SAV community.

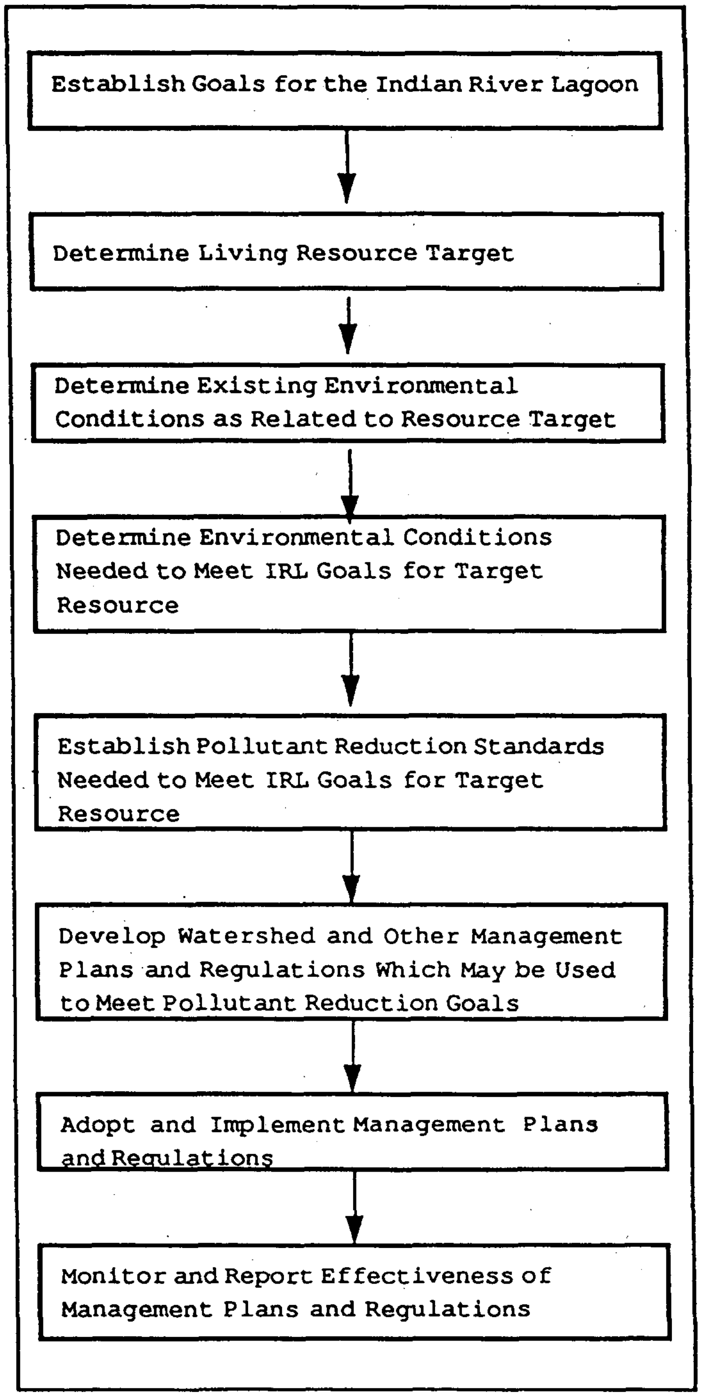
- Established transects to monitor trends in the SAV community as the result of SAV initiative project.

- Develop resource based standards for each segment using SAV light availability models and information collected through the water quality and PAR monitoring program.

- Develop needed watershed management practices to meet Indian River Lagoon SAV standards.

In general, the SAVI can be easily understood as follows:

FIGURE A-1
Establishing the Submerged Aquatic Vegetation Initiative



The Management Conference projected products for the SAV initiative include:

-Inventory of SAV throughout the Indian River Lagoon system.
-Analysis of factors causing loss of SAV.
-Recommendations for controlling factors causing SAV decline.
-Recommendations for strategies and methodologies to maintain existing SAV habitat and restoration or rehabilitation of SAV in impacted areas.
-Recommendations for continued assessment of SAV.

SAVI PROJECTS AND PROJECT DESCRIPTIONS

FY '91 & '92
- FY '91 SAV mapping
- Hydrodynamics-Circulation, Salinity and Discharge

FY '92
- Characterization Report SAV Mapping

FY '93
- Bathymetric Mapping
- WQ Trends, Toxins, In-place Loadings
- Segmentation
- Light Availability Model
- Monitoring Network
- Demonstration Projects

FY '94
- Calibration
- Light Availability Model
- Monitoring
- Demonstration Projects

FY '95 & '96
- Watershed Management Strategies
- Adoption and Implementation of Water Quality Standards
- Monitoring
- Demonstration Projects

The following projects are designed to accomplish the goal, objectives and strategies of the SAVI:

SAV Mapping

Through the use of aerial photography, the extent of SAV coverage in the Indian River Lagoon will be determined on a regular basis. This project will involve interpretation of these photographs, ground-truthing SAV beds noted in the interpretation process, production of maps of SAV coverage, and digitization of these maps into a geographic information system.

Bathymetric Mapping

Aerial photographs will again be used to develop fine scale bathymetrics maps of the Indian River Lagoon. Photos will be interpreted to develop depth contours which will be ground-truthed. Following the interpretation, ground-truthed maps will be produced which will be digitized for use in a geographic information system.

Segmentation Determination

Through this project, a scheme for dividing the lagoon into homogeneous segments for analysis and management purposes will be developed. Information considered in this process will include, at a minimum, bathymetric and SAV maps, PAR data, water quality data, pollutant loading information and hydrodynamic information.

Water Quality and PAR monitoring Networks Revision

Through the cooperation of local governments, a water quality monitoring program has been developed and is operational throughout the Indian River Lagoon. To accomplish the purposes of the SAVI, this monitoring network will probably need to be modified or a new network developed tailored to the needs of individual segments.

The SAVI network may require additional stations sampled at greater frequency but the number of parameters measured may be reduced.

SAVI Light Availability Model Calibration

The models to be used to develop water quality standards for each segment were initially developed for Hobe Sound area. As a result, the models may need to be calibrated for individual segments or general areas.

Data generated by the sampling program within the segment or general area will be used to modify the model to fit local conditions.

Application of the SAV Light Availability Model

Using the calibrated SAV Light Availability model and data collected through the monitoring program, resource-based standards will be developed for each segment. The model will also identify the primary pollutant to be targeted for corrective action in each segment.

Development of Watershed Management Strategies

As resource-based standards are developed for a segment, management strategies may be developed to meet this standard. These strategies may incorporate revisions, and implementation of the technologies tested as part of pilot projects to the lagoon.

Adoption and Implementation of Strategies

At this stage, management strategies developed by the various levels of government would be adopted and implemented. Activities in this period could be as diverse as rule adoption and enforcement to construction of pollution abatement facilities.

Monitoring Effectiveness of Strategies

Through ongoing monitoring of water quality and SAV mapping, the effectiveness and progress of watershed management practices towards meeting the SAVI goal would be determined. Based on the results of the ongoing monitoring program, adjustments may be made as needs to management strategies.

CONCLUSION

The SAVI will serve as a coordinating theme and course of actions for the longterm restoration of the Indian River Lagoon through the IRLNEP. Restoration will be accomplished by developing a meaningful standard which the public and local governments can easily understand and utilize. This standard, related directly to watershed management activities, will have a demonstrable positive impact on the lagoon. This work may be easily shown as moving toward restoring the lagoon to a more pristine state. In contrast, current standards are often interpreted as allowing for varying levels of degradation.

The development and implementation of the SAVI will require a cooperative effort between federal, state and local governments and jurisdictions which create an avenue for the cooperative development of a long-term management plan for the lagoon.

APPENDIX II

APPENDIX II

DO FEDERAL WATER QUALITY CRITERIA AND FLORIDA STATE WATER QUALITY STANDARDS PROTECT SEAGRASS?

A FEASIBILITY EVALUATION OF ALTERNATIVE CRITERIA AND STANDARDS TO MONITOR EVALUATE AND REGULATE WATER TRANSPARENCY

INTRODUCTION

GENERAL BACKGROUND

The cumulative effects of man's continued and growing presence in the coastal zone impact the quality of river, estuarine and nearshore waters. An important aspect of water quality affected by man's activities is water transparency. The amount of light available to support primary production is directly dependent on the transparency of water and is especially critical for benthic seagrasses which are usually growing in anoxic sediments. Whereas, phytoplankton are readily mixed up into the photic zone, seagrasses remain attached to the bottom, making them especially vulnerable to the adverse effects of decreased water clarity.

Relatively large scale declines in the distribution and abundance of seagrasses have been attributed to the attenuations of light associated with poor water quality (Lewis *et al.*, 1983; Orth and Moore, 1983; Wetzel and Penhale, 1983; Cambridge and McComb, 1984; Livingston, 1987). The areal magnitude of these declines, for example a 50% reduction in seagrass habitat in Tampa Bay and a 75% decline in the Virginia waters of Chesapeake Bay, suggest that large scale displacements of primary and secondary production can be mediated by poor water quality.

Turbidity is a generic water quality term loosely referring to the extent that water lacks clarity (Kirk, 1983). The clarity or transparency of water depends on the optical properties which also affect visibility, heating, stratification and biogeochemistry. For primary production, the most important turbidity characteristics of water are the properties which attenuate irradiance in the photosynthetically active wavelengths between 400 and 700 nm (PAR). PAR is an essential requirement for photosynthesis, growth and the reproduction of all primary producers. The amount of PAR and its penetration in a water body depend on two properties, scattering and absorption. These two inherent optical properties of the water are additive and depend on the suspended and dissolved constituents such as sediments, chlorophyll and dissolved organic matter (Preisendofer, 1961. Kirk, 1983; Kirk, 1988). Thus, in order to protect seagrasses, water quality criteria and standards must target the monitoring and regulation of these constituents (Orth *et al.*, 1991).

For seagrasses, the availability of PAR determines the magnitude of their production and biomass as well as the depth at which different species can grow (Dennison, 1991; Duarte, 1991). Reported trends for a correspondence between water turbidity, deteriorating water quality and the decline of seagrasses suggest two important issues. Either water quality criteria a nd standards are inadequate for the protection of seagrasses, or their implementation is not effective. The objectives of this chapter are to: 1) review and evaluate the capability of federal water quality criteria to protect seagrasses; 2) evaluate the capability of the Florida transparency and turbidity standards to protect seagrasses and; 3) discuss. the feasibility of developing an alternative transparency standard based on the attenuation of photosynthetically active radiation (PAR) and the biological and ecological characteristics of seagrass growing in the southeastern United States and Caribbean Basin.

HISTORICAL BACKGROUND

Now known as the Clean Water Act (CWA), the original Federal Water Pollution Control Act (FVPCA) authorized states and the federal government to establish water quality standards for the control and abatement of water pollution. Development of the original guidelines for formulating state standards and criteria began with the Water Quality Act of 1965. This Act specified that water quality standards submitted by the states were subject to review and approval by the Department of Interior. Furthermore the Act specified that if a state did not adopt standards consistent with the language of the Act, the Secretary of the Interior was allowed to set the standards. Recognizing the responsibilities associated with this authority the Secretary of the Interior established the National Technical Advisory Committee on Water Quality Criteria (NTAC). The objectives of the NTAC were to collect into one volume a basic foundation of water quality criteria and to summarize research needs in the area of criteria development.

The result of the committee's efforts were published as the "Green Book" (National Technical Advisory Committee to the Secretary of the Interior, 1968). This is an important document because it contains much of the narrative and numerical information that either did, or should have gone into formulating the Quality Criteria for Water published in 1976 by the Environmental Protection Agency (EPA) and generally known as the "Red Book" (Environmental Protection Agency, 1976).

Publication of the "Red Book" marked the transfer of responsibility from the Department of the Interior to the newly established EPA. The Federal Water Pollution Control Act Amendments of 1972 required the Administrator of the EPA to publish water quality criteria accurately rending the latest scientific knowledge on the kind and extent of all identifiable effects on health and welfare which may be expected from the presence of pollutants in any body of water. within section 304 of the amendments it was specified that these criteria consider the factors necessary for the protection of fish and wildlife and the criteria were to be revised, from time to time based on the latest scientific knowledge. In this transition some important information contained within the "Green Book" was not incorporated into formulating criteria in the "Red Book". An example of this is the matter of light penetration and transparency.

The original "Green Book" addressed turbidity and color in two section: 1) Fresh Water (p. 39) and: 2) Marine and Estuarine Organisms (p. 66); while light penetration was addressed in a section entitled Wildlife (p. 93). The narrative on turbidity in the Fresh Water section did not address submerged vascular plants but the section on color did. The narrative on color specified that the compensation point for some submerged aquatic plants could be maintained at 5% of full sunlight on clear summer days but that 25 to 50% of full sunlight is necessary for many green aquatic plants to reach maximum photosynthesis. The NTAC recommended that 10% of the incident light should reach the bottom of any desired photosynthetic zone in which aquatic dissolved oxygen levels are to be maintained.

In the Marine and Estuarine section of the "Green Book" regarding turbidity, the narrative specified that the compensation intensity for marine phytoplankton was 1% of the value of full sunlight and the role of phytoplankton was far more quantitatively important than benthic plants. Thus, no value for marine aquatic vascular plants was specified in the turbidity or color narratives of this section. This is not surprising, since the "Green Book" was published prior to the general recognition that seagrasses are extremely important coastal ecosystems. Despite the evidence presented in work from earlier in the century (Ostenfeld, 1908; Petersen and Boysen Jensen, 1911), it wasn't until 1973 that the First International Seagrass Workshop held in the Netherlands drew worldwide scientific attention for the value of seagrass ecosystems (McRoy and Helefferich, 1977).

The most comprehensive and specific discussion of light penetration was located in the Wildlife section of the "Green Book" and reads as follows:

"Algae, turbidity from silts and clays, and color of the water all affect one environmental factor of major importance in the productivity of aquatic wildlife habitats-light penetration of the water. The results of many of man's activities, including agriculture, industry, navigation, channelization, dredging, land modification, and eutrophication from sewage or fertilizers, often reduce light transmission to the degree that aquatic angiosperms of value to wildlife cannot grow.

Bioassays and field studies by Bourn (1932) and Sincock (unpublished data) demonstrated that at least 5% of the total incident light at the surface was required for growth of several aquatic plants (as measured while the sun was near its apex, between 10 a.m. and 2 p.m.). Optimum production occurred where 10 to 15% of the light reached the bottom. Most aquatic plants will grow In water depths of 6 feet or more if sufficient light Is available. For optimum growth in aquatic wildlife habitats the light at the 6-foot depth should be 10% of incident light at the surface; tolerable limits would be 5% of the light at the surface at the same depth. In situ determinations of light penetration, as measured with a subsurface photometer, provide the best indication of suitability for plant growth.

Observations have indicated that prolonged exclusion of adequate light results in the destruction of submerged aquatic plants; the period during which the plants must endure less than 5% of the incident light at the surface should probably not exceed 7 consecutive days if they are to survive.

Of course, light penetration and the factors affecting it; e.g. turbidity, color and algal concentrations, vary in intensity daily, seasonally, and annually. in most areas, submerged aquatic plants die back in the fall and winter and the quantity of light required becomes less critical as a requirement. In the spring and summer, however, sufficient light Is imperative to growth."

Clearly, the value of aquatic vascular plants is recognized in this narrative and the light requirements are specified as being higher then those for phytoplankton. Furthermore, this narrative identifies a lethal sub-compensation dose level not to exceed 7 consecutive days of light less then 5% of the incident. Other important aspects of the narrative are the recognition that sources of light attenuation and the light requirements of aquatic plants vary seasonally. ***"The NTAC recommended: For optimum growth of aquatic food plants, at least 10% of the Incident light at the water surface should reach a depth of six feet. light penetration to this depth should not be less than 5% of the incident light."*** Between all these references to light penetration in the "Green Book" many of the essential ingredients of a transparency or turbidity standard needed for the protection of seagrasses were present. Even though the discussions on color and turbidity in the Marine and Estuarine Organisms section overlooked the importance of aquatic vascular plants, the material provided in the wildlife section did identify the need to protect them. Unfortunately, neither transparency or light penetration were adopted as specific criteria in the EPA "Red Book". However, narrative and numerical references to light penetration and transparency are found in two related criteria: 1) Color (p. 81) and; 2) Solids (suspended, settleable) and Turbidity (p. 210). The most detailed language is found in the color criteria and read as follows: ***"The effects in water on aquatic life principally are to reduce light penetration and thereby generally reduce photosynthesis by phytoplankton and to restrict the zone for aquatic vascular plant growth. The light supply necessary to support plant life is dependent on both intensity and effective wave lengths (Welch, 1952). in general, the rate of photosynthesis Increases with the intensity of the incident light. Photosynthetic rates are most affected in the red region and least affected in the blue-violet region of the Incident light (Welch, 1952). it has been found that In colored waters the red spectrum is not a region of high absorption so that the effective penetration, and therefore the intensity for photosynthesis is not restricted to other wavelengths. It should be emphasized that transmission of all parts of the spectrum is affected by color, but the greatest effect is on the shortwave or blue end of the spectrum (Birge and Juday, 1930). In highly colored waters (45 to 132 color units) Birge and Juday (1930) measured the light transmission as a percentage of the incident light and found very little blue, 50% or less yellow, and 100 to 200% red.***

The light intensity required for some aquatic vascular plants to photosynthetically balance the oxygen used in respiration may be 5% of full sunlight during maximum summer Illumination periods (NTAC, 1968). As much as 10% of the incident light may be required for plankton to likewise photosynthetically produce sufficient oxygen to balance their respiration requirements (NTAC, 1968). The depth at which a sub-compensation point Is reached, called the compensation depth, delineates the zone of effective photosynthetic oxygen production. To maintain satisfactory biological conditions, this depth cannot be substantially reduced from natural conditions.

Several aspects of the narrative in this criteria are worth addressing. First of all, the NTAC stated specifically in the freshwater section that the compensation depth for phytoplankton was 1%. In the development. of the EPA color criteria numerical values of light penetration in the Wildlife section of the "Green Book" were presumably adopted, yet the "Red Book" assigned a higher compensation light requirement for plankton (10%) than for vascular plants (5%). However, more recent studies suggest that the value for seagrasses is at least as great as, or greater than, 10% (Dennison, 1987, 1991; Duarte, 1991; Kenworthy and Haunert, 1991). In addition, the EPA color criteria does not establish a lethal sub-compensation light level, leaving the criteria with very little guidance as to how long the plants could survive exposure under the recommended numerical values.

In the solids and turbidity criteria found in the EPA "Red Book", language referring to light penetration reads as follows: ***"Plankton and inorganic suspended materials reduce light penetration into the water body, reducing the depth of the photic zone. This reduces primary production and decreases fish food. The NAS committee recommended that the depth of light penetration not be reduced by more than 10% (National Academy of Sciences, National Academy of Engineering, 1974)."*** Although the narrative in this section does not refer specifically to the compensation depth, this may actually be the source of information for the allowable 10% reduction in the Florida transparency standard (see next section).

Since implementation of the FWPCA and publication of the "Green" and "Red" books, quantitative scientific information on the light requirements of seagrasses and the effects of light attenuation on seagrass growth are available (Kenworthy and Haunert, 1991). During the past 15 years, and especially since the Florida transparency standard was written, knowledge of the light requirements of seagrasses and the sources and effects of water turbidity greatly exceed the information contained within the Federal Criteria and the Florida Standards. in the next section I evaluate the two Florida standards pertaining directly to water clarity and discuss the measurement of transparency by secchi disc depth. I evaluate these criteria and methods on the basis of the more recent scientific information that provide numerical values for the characteristics of the submarine light environment and minimum light requirements of seagrasses. I also incorporate basic ecological information on the seagrass species which can be used to develop criteria that have a solid biological foundation.

EVALUATION OF THE FLORIDA TRANSPARENCY AND TURBIDITY STANDARDS

DEFINITIONS

Florida's standards are intended to promote water quality sufficient to maintain a designated use. According to Chapter 17-3.021 ***"Designated use shall mean the present and future most beneficial use of a body of water as designated by the Environmental Regulation Commission by means of a classification system contained in Chapter 17-3."*** Surface waters in Florida are classified into 5 categories: 1) Class I-Potable Water Supplies, 2) Class II-Shellfish Propagation, 3) Class III-Recreation Propagation and Maintenance of a Healthy, Well Balanced Population of Fish and Wildlife, 4) Class IV-Agricultural Water Supplies and, %) Class V-Navigation, Utility and Industrial Uses. For this discussion I will be addressing only those criteria or standards applicable to Class III waters.

Within Chapter 17-3 of the Water Quality Standards of Florida the State has two water quality criteria pertaining directly to turbidity or clarity of water. These are 1) turbidity measured by nephelometric turbidity units (NTU) and 2) transparency based on irradiance measurements. These standards are written as follows

> ***"(1). In 17-3 Surface Waters: General Criteria paragraph (3r) Turbidity - shall not exceed 29 Nephelometric Turbidity Units above natural background. A violation of this criteria constitutes pollution.***
>
> *(2). In 17-3.121: Class III Waters* ***Recreation-Propagation and Maintenance of a Healthy Well Balanced Population of Fish and Wildlife paragraph (28), Transparency-the depth of the compensation point for photosynthetic activity shall not be reduced by more than 10% compared to the natural background value."***

Under 17-3.02 1, the definition pertaining to the terminology in these standards read as follows:

> ***"paragraph (3), 'Background' shall mean the condition of waters in the absence of the activity or discharge under consideration, based on the best scientific information available to the department;***
>
> ***paragraph (18), 'Natural Background' shall mean the condition of the waters in the absence of man-induced alterations based on the best scientific Information available to the Department (the establishment of***

natural background for an altered water body may be used upon a similar unaltered water body or on historical pre-alteration data); and

paragraph (6), "Compensation Point for Photosynthetic Activity" shall mean the depth at which one percent of the light Intensity at the surface remains unabsorbed. The light intensities at the surface and subsurface shall be measured simultaneously by irradiance meters such as the Kahlsico Underwater Irradiameter, Model No. 268 WA 310 or other devices with comparable spectral response."

TRANSPARENCY STANDARD

Florida is the only coastal state in the U.,S. that has adopted a transparency standard. Because of an overwhelming tendency to emphasize turbidity rather than transparency, the general public, scientists, resource managers and other personnel in private organizations and state and federal agencies are not even aware of the existence of this transparency standard. Most water clarity measurements are obtained by either Nephelometric Turbidity Units (NTUs), Jackson Turbidity Units (JTUs) or secchi disc transparency (secchi disc depth). Equally important is the fact that the water quality database, Storet, does not even include a transparency parameter specified by the type of measuring equipment described in the transparency standard's narrative. Yet, the transparency standard recommends measurement equipment which quantifies PAR, and this has much greater potential value for protecting seagrasses than either NTU or secchi disc depth.

There are at least six problems with the transparency standard regarding the protection of seagrasses: 1) The numerical value for the definition of the compensation point (1%) does not apply to seagrasses; 2) The 10% allowable reduction, if maintained, could have very substantial negative impacts to seagrasses; 3) Values for time periods of allowable sub-compensation light levels are not specified; 4) Background must be more precisely defined by incorporating water quality management goals; 5) Background values fluctuate spatially and temporally and: 6) Application of a general standard to different water bodies with characteristically different background water quality, different bathymetry and different species composition is inappropriate and oversimplified. I will first address each of these six problems in a brief general discussion and follow this by proposing an alternative model for evaluation in the final sections of this chapter.

DEFINITION OF THE COMPENSATION POINT

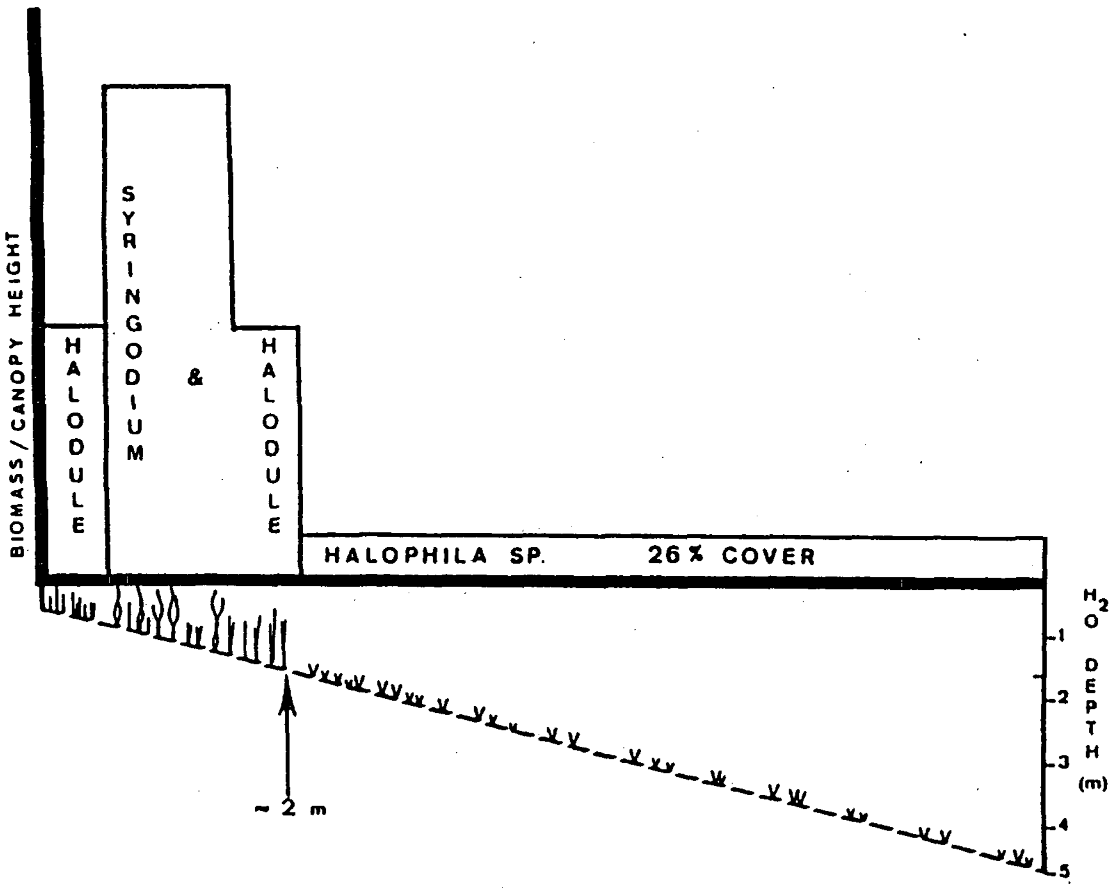
The seagrass communities of Florida, the southeastern U.S. and the Caribbean Basin can consist of as many as seven species including *Thalassia testudinum, Halodule wrightii, Syringodium filiforme, Halophila decipiens, Halophila engelmanni, Halophila johnsonii,* and *Halophila ballonis.* The highest diversity of seagrasses in the continental United States occurs in the southern Indian River Lagoon between Fort Pierce Inlet and Jupiter Inlet in Lake Worth, and south to Virginia Key in northern Biscayne Bay where the species frequently occur except for *Halophila ballonis.* Studies of different species depth distributions in the field, laboratory physiological data, and whole plant carbon balance modeling indicate these six species of seagrass can be grouped into three associations with different minimum light requirements (Fourqurean and Zieman, 1991: Kenworthy and Haunert, 1991: also see Chapters 1, 2, and 3). In developing, or recently established seagrass communities, or in environments with elevated temperatures, *T. testudinum* has the highest light requirement. However, in the climax or fully developed *T. testudinum* system the light requirements for this plant may be lowered because of its large below ground carbohydrate storage reserves (Dawes and Lawrence, 1980: Hall *et al.*, 199 1). In a mature stand with extensive root and rhizome biomass, *T. testudinum* may be able to utilize below ground carbohydrate reserves for survival during moderate or extended periods of light limitation. But, in order to grow and form this larger below ground storage material, to reproduce, and to successfully colonize an area, *T. testudinum* would require relatively more light than other species in the initial stages of development.

H. wrightii and *S. filiforme* have similar minimum light requirements which as intermediate between the requirements of *T. testudinum* and the smaller *Halophila* species. Generally, the *Halophila* species, *H. engelmanni* and *H. decipiens*, grow in deeper and more turbid waters and have distinctive morphological and life history characteristics adapted to relatively lower or fluctuating light environments. The recently described species, *H. johnsonii*, may be a special case for this genus. *H. johnsonii*, grows in the shallow inter-tidal as well as in the lower sub-tidal in association with *H. decipiens* (see Chapter 1). A generalized model of the depth distribution of these six species in the Indian River may be applicable throughout the turbid continental margins of the southeastern United States (Figure A-1). Shifts toward deeper depths, but with the same relative species zonation patterns have been reported in the Big Bend Region of the eastern Gulf of Mexico, the Florida Keys and the clear oligotrophic waters of the Caribbean Basin (Buesa, 1974; Wiginton and McMillian, 1979; Zieman, 1982; Continental Shelf Associates, Inc. and Martel Laboratories, Inc., 1985; Iverson and Bittaker, 1986; Zieman and Zieman, 1989; Kenworthy and Haunert, 1991). Generally, *T. testudinum* does not extend to the deepest limits of the beds and in turbid water it is constrained to shallow depths. *H.*

wrightii grows in both shallow and deep water while *S. filiforme* distribution overlaps with *H. wrightii* in the intermediate and deeper depths (Figure A-2). Where these three species co-occur and environmental conditions are optimum for *T. testudinum*, the larger climax species may displace *H. wrightii* and *S. filiforme* at the immediate depth ranges (Iverson and Bittaker, 1986; Williams, 1988; Zieman and Zieman, 1989).

Healthy leaves of the six species of seagrass will photosynthesize in 1% incident light or absolute values equivalent to 10 to 50 µE (Dawes *et al.*, 1989; Fourqurean and Zieman, 1991; Chapter 3). However, the whole plants cannot sustain growth and reproduction at these low light levels for extended periods of time. Minimum light levels required for growth, reproduction and population maintenance are in excess of 10 to 15% of the surface incident light based on an annual average and will vary by species (Iverson and

Figure A-2. Hobe Sound Seagrass Depth Distribution



Bittaker, 1986; Zieman and Zieman, 1989; Duarte, 1991; Kenworthy and Haunert, 1991). The basis for this higher requirement, compared to the traditional 1% photic zone, is the fact that seagrasses have extensive non-photosynthetic root and rhizome biomass growing in chronically anaerobic sediments. The light required for the photosynthetic leaves to balance the respiratory needs of the whole plant is much higher than for the leaves alone. Their whole plant light requirement will depend on the relative apportionment of biomass into leaves and non-photosynthetic tissue (Zimmerman *et al.*,1989; Fourqurean and Zieman, 1991). Thus, compensation light values originally cited in the NTAC "Green Book," 5-10% of surface incident light, were more appropriate for seagrasses than the 1% value adopted by the Florida transparency standard.

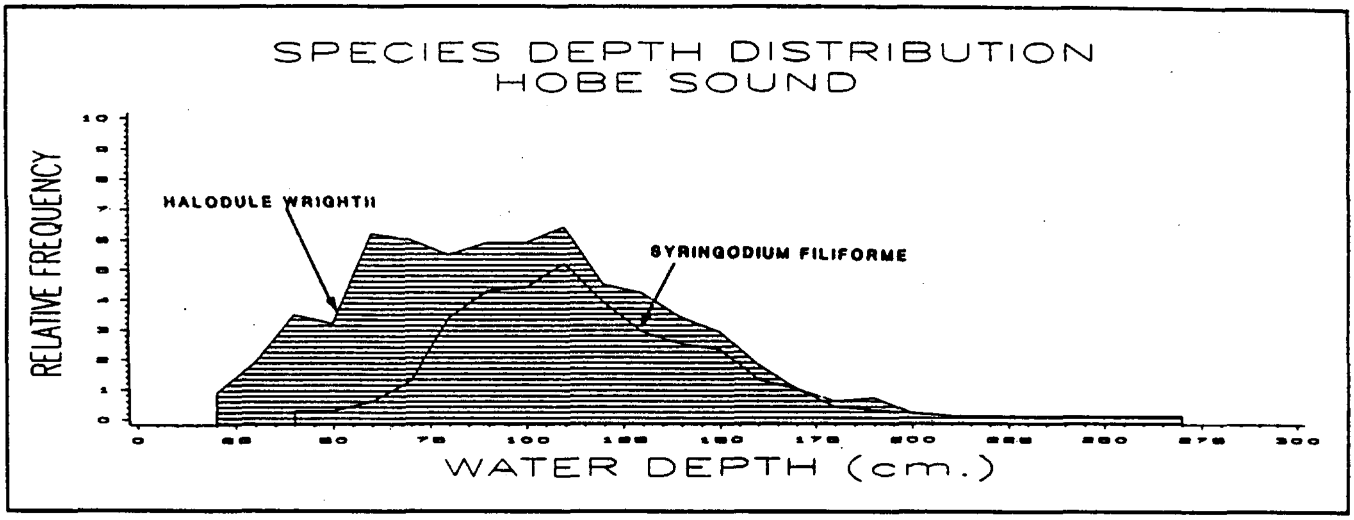
TEN PERCENT ALLOWABLE REDUCTION IN THE COMPENSATION DEPTH

This allowance could lead to a very large retreat in the lower depth distribution and areal extent of seagrasses in lagoons and coastal plain estuaries which have small bottom slopes like the Indian River. For example, the ecological compensation depth for two seagrasses in the interior lagoon of Hobe Sound, *H. wrightii* and *S. filiforme,* is approximately 1.75 cm to 2.0 m (Figure A-3). The bottom slope in this lagoon is 2cm/m. Based on this slope a 10% reduction in the compensation depth is a 17.5 to 20 cm depth change. A slope of 2cm/m translates into an 8.75 m shoreward retreat of the compensation depth (based on 17.5 cm). If a 10% reduction were maintained in a lagoon such as Hobe Sound which is 5 km long, this would allow a loss of as much as 43,750 m^2, or 10.8 acres of seagrass. Because of the possible consequences of this allowance, and the absence of a clause specifying the time allowed for such a reduction (see item 3), there is a potentially large resource loss built into the existing transparency standard. Given the specific language of the federal anti-degradation policy (Federal Register, Vol. 48, No. 217, November 8, 1983), the policies of many state and federal resource agencies consider such a loss unacceptable. This standard may actually fail to maintain the *status quo,* and given the known vegetative growth and coverage rates of these two species of seagrass (Fonseca *et al.,* 1987), it could take 3-5 years to recover the 8.75 m retreat if water transparency were restored to previous conditions. This simple exercise demonstrates a severe weakness in the transparency standard as it is now written.

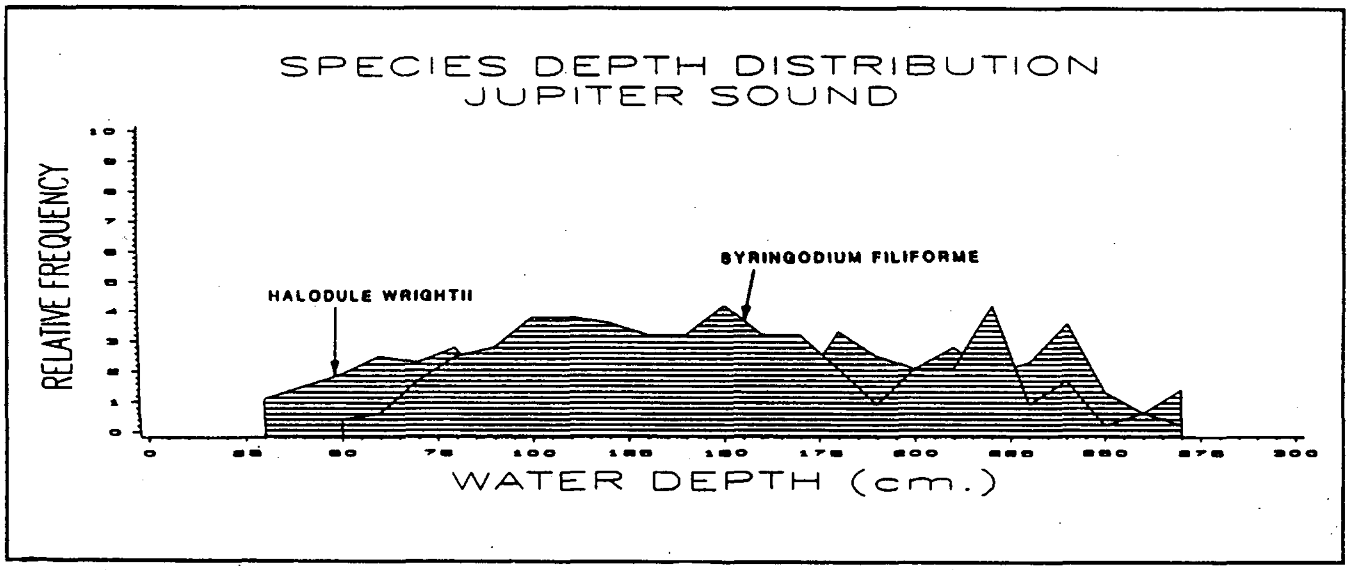
TIME PERIOD FOR ALLOWABLE SUB-COMPENSATION LIGHT LEVELS

The transparency standard fails to identify the time period for which the allowable reduction can be safely maintained. As it is written, the standard may be interpreted

Figure A-3. Illustration of the overlapping depth distribution of *Halodule wrightii* and *Syringodium filiforme* in two lagoons in the southern Indian River Lagoon, Florida.



Species Depth Distribution Jupiter Sound



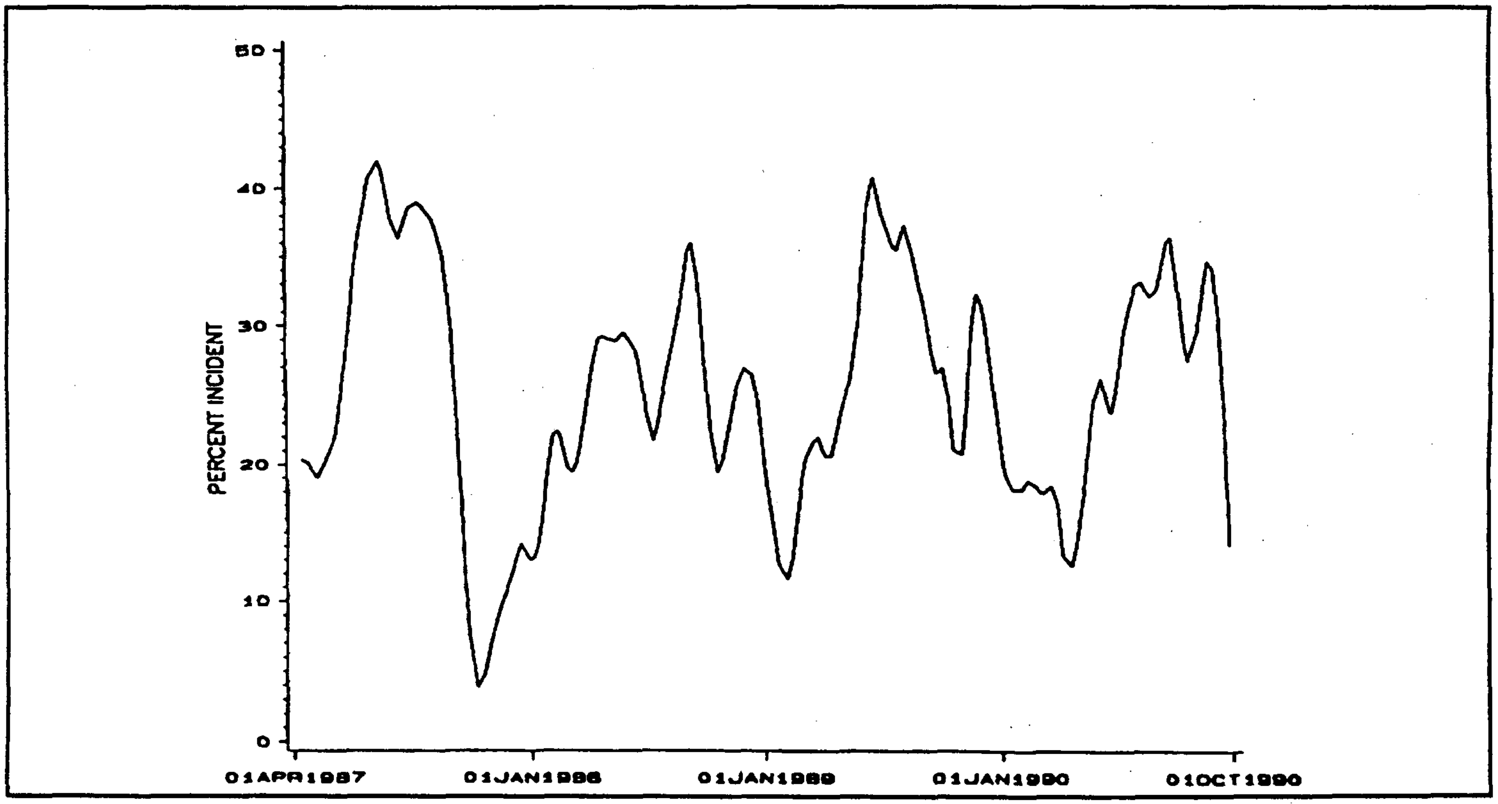
to allow unlimited time and the possibility for extended periods of light limitation. Because of the differences in their life history, morphology and biomass allocation, there should be predictable differences in the response of seagrasses to a reduction in light. The species with the lowest carbohydrate reserves and the highest respiration rates should be more susceptible to extended periods of low light. Based on laboratory studies, *H. wrightii* has the highest metabolic rates, *S. filiforme* the next highest and *T. testudinum* the lowest (Fourqurean, 1987; see Chapter 3). Comparable values for the three *Halophila* species have not yet been obtained. However, because of the evidence for the allometric scaling of seagrass growth (Duarte, 1991: see Chapter 1) it species have higher is likely that the metabolic rates.

With the lowest respiration rates and the higher storage biomass of the three major canopy species (Dawes and Lawrence, 1980; Dawes, 1987), a mature *T. testudinum* bed may be able to survive longer periods of sub-compensation light levels than the other species. A recently completed shading study of *T. testudinum* demonstrated a nine to twelve month lag time in the response of *T. testudinum* to a 60-65% reduction in light at the deep edge of a meadow (Hall *et al.*, 1991). Unfortunately there are no comparable shading studies for the remaining six species in the southeastern United States. However, response times in shading studies of temperate species with proportionally less non-photosynthetic biomass (e.g. *Zostera* and *Heterozostera*) occurred much more rapidly than *T. testudinum*. This suggests that the effects of long-term light reduction are species specific (Beckman and Barilotti, 1976; Congdon and McComb, 1979; Buithuis, 1983). *H. wrightii* exhibits a higher efficiency of light utilization at lower light levels as well as a higher maximum photosynthetic rate than either *S. filiforme* or *T. testudinum* (Fourqurean, 1987, see Chapter 3) suggesting that its photosynthetic physiology may be capable of offsetting the consequences of diminished light levels. However, since these two species and *Halophila* spp. have much lower root and rhizome storage capacity, I predict that a longterm reduction in light will have a faster detrimental effect on established *H. wrightii, S. filiforme,* or *Halophila* spp. meadows. This prediction is largely based on the expected function of carbohydrate storage in minimizing the negative consequences of light reduction. The model assumes that storage carbohydrates are important but what remains to be determined is the relative dependence of seagrasses on current photosynthate versus stored carbohydrates and how this dependence changes with time of year and temperature regime.

DEFINITION OF BACKGROUND AND BACKGROUND FLUCTUATION

It is necessary to quantify temporal and spatial variation in background transparency (Figure A-4). As shown in more detail in Chapter 2, these fluctuations have large signatures and there are distinct spatial patterns that reveal the sensitivity of seagrasses to changes in average annual attenuation. Background values also require an understanding of the individual species response. Because most coastal water bodies

Figure A-4. Percent Light at Two Meters Depth in Hobe Sound



have been impacted, background can only be defined as an already deteriorated *status quo*. Water quality management goals should be defined which identify true or acceptable background value's and realistically achievable transparency values for specific depths and desired seagrass species. Accepting the current background conditions may limit overall expectations and diminish restoration efforts.

APPLICATION OF A GENERAL STANDARD

Because water bodies vary in their sources of turbidity, bathymetry, and seagrass composition, a general standard will fail to adequately protect seagrasses. Scientifically based water quality goals should be defined by the bathymetry, the seagrass species desired, and realistic areal coverage goals Because of the constraints inherent in most water management programs, site or region specific standards will be more effective in protecting seagrasses. Also, the standards should directly address the factors responsible for light attenuation, including total suspended solids, chlorophyll, dissolve organic matter (color) and dissolved inorganic nutrients. Criteria and standards should be integrated into an overall management plan for individually targeted watersheds.

TURBIDITY STANDARD

The greatest drawback to a turbidity standard based on a measure of NTUs is that it does not assess total PAR attenuation. In addition, there are no empirically derived biological relationships between the measurement of NTU and seagrass growth or depth distribution by secchi disc depth and quantum sensor (Dennison, 1987; Giesen *et al.*, 1990; Duarte, 1991). NTU's quantify scattering, which is only a portion of the total equation for light attenuation. The total equation consists of absorption and scattering and both should be measured in order to completely assess the light regime and determine the potential sources of attenuation (Kirk, 1983; McPherson and Miller, 1987: Vant, 1990; Gallegos *et al.*, 1990).

SECCHI DISC DEPTH

The secchi disc depth has been used for more than a century as a simplified measurement to describe water transparency. Several studies have reported a close correspondence between the secchi disc depth and the depth to which seagrasses grow (Beckman and Barilotti, 1976; Vincente and Rivera, 1982; Dennison, 1987; Giesen *et al.*, 1990; Duarte, 1991; Dennison, 1991). Conversions from secchi disc depth to the light attenuation coefficient (*K*) have been formulated worldwide and have lead to the development of simple regression models relating the estimated *K* value to seagrass depth penetration (Poole and Atkins, 1929; Giesen *et al.*, 1990: Dennison, 1991). Unfortunately, most of the conversion coefficients were developed for clear oceanic water. More recent examination of coefficients derived for estuarine environments have revealed the potential errors due to water color (DOM) when estimating *K* from the secchi disc (see Chapter 2). The disc is actually measuring an apparent property of the water column and is subjected to the errors introduced by the eye of each of the observers as well as the properties of the water column. The most influential property, water color (dissolved organic matter), alters the spectral composition of the submarine light regime. Colored waters absorb strongly in the shorter wavelengths and transmits a considerable amount of light in wavelengths near the maximum sensitivity of the human eye (around 550 nm). Therefore, the eye will report a higher transparency than a photoelectric sensor which responds to all PAR wavelengths equally. This discrepancy will lead to lower estimates of light attenuation in colored water when using the secchi disc. The other major problem with the disc is the fact that in moderately clear shallow water the disc frequently is seen while resting on the bottom, thus an estimate of the *K* value cannot be made.

GENERAL CONSIDERATIONS

In addition to these technical and quantitative considerations, there are problems with the general application and implementation of a standard. Standards seem to have been developed for and are frequently applied to, point sources of pollution rather than the more subtle and difficult to quantify non-point sources (Kirk, 1988). In order to protect seagrasses a transparency standard must have a broader application to the many sources of pollution that impact light attenuation. The standard must incorporate a consideration of sources which both absorb and scatter PAR and be capable of both diagnosing a light attenuation problem as well as providing basic information on the potential sources of attenuation. The standard must also be flexible enough to incorporate the different light requirements of each of the seagrasses and not favor the protection of any particular species.

DISCUSSION OF AN ALTERNATIVE TRANSPARENCY STANDARD TO PROTECT SEAGRASSES

GENERAL BACKGROUND

In order to adequately protect seagrasses a transparency standard should have the following attributes: 1) the numerical value(s) must be based on the ecological light compensation point (ECP) of the target species., 2) the standard must be flexible enough to account for differences in the light requirements between species as well as the different characteristics of coastal watersheds., and 3) the diagnostic parameter must be easily acquired and quantitatively related to water quality parameters which have a functional relationship to the growth and survival of seagrasses.
Utilizing an ECP, rather than a leaf compensation point, more accurately reflects the light requirements of a species. An ECP goes beyond recognizing the mere survival of a leaf and incorporates the respiratory maintenance of non-photosynthetic tissue, plant reproduction, and life history strategies. Many seagrasses, including all of the species growing in Florida, reproduce asexually and extend their areal distribution by vegetative reproduction, branching, and rhizome elongation. The growth, areal coverage, and overall distribution of *T. testudinum, H. wrightii* and *S. filiforme* are primary determined by their asexual reproductive strategy and are correlated with their ability to sustain the respiratory and physiological demands of root rhizome metabolism, reproduction and growth in chronically anaerobic sediments. The areal extent and depth penetration of many seagrasses is intricately linked to their primary mechanism of nutrient acquisition (root growth) and population dynamics (rhizome growth).

The most current scientific information suggests that the minimum light requirements of *T. testudinum, H. wrightii* and *S. filiforme* are at least 10 to 15 percent of the surface incident light. These values are based on analyses of zonation patterns along static transects and on annual average values of light attenuation derived from both short and long-term data sets of submarine light (Iverson and Bittaker, 1986; Zieman and Zieman, 1989: Duarte, 1991: Kenworthy and Haunert; 1991; Onuf; 1991; Chapter 2). The ECPs of these species are at least 20% of the incident light and, as mentioned earlier, these requirements may differ according to the stage of maturity in the development of below ground storage reserves or, in the case of *H. decipiens* and *H. engelmanni,* their sexual reproduction strategies. Until further experimental work distinguishes the subtle, but potentially significant differences between the species, a conservative strategy would be to implement a standard protecting the most sensitive species, thus, most other seagrasses would be protected. Protecting species for their

ECP rather then their minimum requirements for survival provides a buffer from extensive mortality due to a sudden, unexpected deterioration in water quality.

Flexibility in the development and application of a standard recognizes local and regional watershed differences in geomorphology, water circulation and seagrass species pools. Standards should be based on realistic water quality goals that are constrained by the bathymetry of a water body, the species and coverage desired, and the cost of managing the watershed to achieve the desired seagrass coverage. In this manner the standard is placed within the larger framework of a resource management plan that realistically assesses the physics-chemical nature of the coastal water body, the availability of seagrass species and overall utilization patterns in the watershed. The standard is based on watershed or water body specific characteristics and not generalized for the entire state of Florida.

A MODEL FOR AN ALTERATIVE TRANSPARENCY STANDARD

The proposed model for improving the transparency standard incorporates a five step process and is intended to be water body specific. 1) In the initial step the areal coverage, the seagrass species pool, and the maximum depth distribution of seagrasses is determined within the targeted water body. This will establish *status quo* for a watershed or water body and can be compared to historical data to asses temporal and spatial trends in the status of the seagrass community. 2) Concurrently, a systematic water quality sampling program is established that incorporates a pilot sampling design to determine the spacing and frequency for measuring the diffuse,attenuation coefficient, *K*. The background value and the average K value are determined from a final sampling plan so that the percent of the incident light reaching any depth in the water body can be estimated. 3) The desirable seagrass coverage goals are established by a management plan. in this step, bathymetric maps of the water body are compared to seagrass. depth distributions to determine what K values would be required to achieve the desired coverage. Ultimately, these desired coverage can be balanced by the cost to achieve the coverage in a resource management plan. 4) The *K* values are related to functional water quality parameters to evaluate which factors are most influential in determining transparency and ultimately, the areal coverage of seagrasses. 5) Once these factors are determined and their sources identified, a plan is implemented to manage the reduction of inputs from the sources considered detrimental to transparency of the water body (Kirk, 1988). The goals of the plan could be oriented toward restoration of seagrass beds and/or long term maintenance of water quality to protect existing resources.

In this model the *K* value is used as a diagnostic tool to determine the status of water transparency and as a predictive tool to estimate the expected coverage of seagrasses under certain specific water quality conditions (see Chapter 2). The *K* value is not the standard. The standards should be based on the water quality parameters which have a functional relationship with the *K* value and ultimately control the distribution and abundance of seagrasses. Based on the most recent scientific information, the water quality parameters that have the greatest influence on transparency and chlorophyll (CHL), dissolved organic matter (color), total suspended solids (TSS), dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) (McPherson and Miller, 1987; Gallegos *et al.*, 1990; Vant, 1990; Kenworthy and Haunert, 1991; Orth *et al.*, 1991). TSS, CHL and color affect transparency directly while DIN and DIP influence water clarity indirectly by stimulating chlorophyll concentrations in the water column or the growth of leaf epiphytes, which in turn diminish the amount of light reaching the seagrasses.

The *K* value integrates many potential sources of light attenuation and alone it would not serve as a very good tool to identify a problem source. As a diagnostic tool, however, it is very useful. It is easily obtained, highly quantitative and relatively inexpensive to acquire. A portable field unit consisting of two quantum sensors, cable, data acqUisition/storage module, and lowing frame can be assembles for under $2,500.00 (U.S. dollars, 1991). This unit has virtually unrestricted deployment potentials. In a small to moderate sized vessel, typical of sampling platforms used in routine water quality sampling programs, a submarine light profile can be obtained in less than five minutes, depending on the water depth. In water less tan five meters deep an entire light profile consisting of 5-7 sampling intervals can be obtained in less than one minute. Therefore, both intensive (station replication) and extensive (estuarine wide) sampling can be achieved. For example, in the first phase of field study in the southern Indian River (Chapter 2), 24 stations were sampled over a 13 km distance in less than three hours, including travel time to randomly selected transect positions. If light sampling is uncoupled from the temporal demands of the other water quality sampling routines, a large number of stations with suitable replications can be managed in a diagnostic program.

Presently there are a number of water quality monitoring programs in Florida that are utilizing this equipment to evaluate water transparency. These are Dade County DERM (see Alleman in Kenworthy and Haunert, 1991), the Mosquito Lagoon sampling program conducted by Bionetics, Inc. in Volusia County, the St. Lucie Monitoring Program under SFWMD SWIM, Hillsborough County, the Florida DNR Aquatic Preserve s Program in the Indian River and the EPA Program in Sarasota

Bay. The collective experience of these monitoring programs can be used to modify or improve the sampling technology and to rigorously test its utility as a water transparency monitoring and management program.

IMPLEMENTING THE MODEL

DETERMINING AREAL DISTRIBUTION, SPECIES POOL AND THE MAXIMUM DEPTH DISTRIBUTION OF SEAGRASSES.

A coordinated national, state, and county effort to quantitatively map the distribution of seagrasses using remote sensing and ground-truth methods is underway (Thomas and Ferguson, 1990). Several estuaries and coastal lagoons in Florida have already been mapped using high resolution aerial photography or satellite imagery (Virnstein and Cairns, 1986, White 1986: personal communication, Ken Haddad, FMRI, St. Petersburg, FL). Plans to use aerial photography for future mapping programs and continuous tong term assessments of the status of seagrass distribution are being pursued by several state, federal and local resource management agencies. Through programs like NOAAs C-CAP, EPAs EMAP and National Estuary Programs, Coastal Zone Management Programs, the National Marine Sanctuary Program, and the initiatives in SWIM, these distribution maps will be available for water quality programs in a functional GIS format. The entire Indian and Banana rivers have been photographed and mapped and plans are underway to continue the process on a regular basis.

Maximum depth distributions and other ground truth procedures should follow the methods described in Chapters 1 and 2 of this dissertation. In the ground truth phase, field parties are deployed to asses the species pool and maximum depth distribution of seagrasses. The remotely sensed distribution maps (aerial photography or satellite imagery) can be utilized to located station and transect positions. Stratified random sampling along predetermined transects can be employed to make determinations of the water depths and species pools. Historical data for seagrass distribution and water quality may be available in the literature or in data archives and should be used to verify current survey and to estimate temporal and spatial trends in seagrass distribution and abundance. Preferably, long-term permanent transects should be established for repeated monitoring of changes in depth and species distributions. These stations should be coordinated with the positioning of water quality monitoring stations so that *K* value versus seagrass depth (and species) relationships can be established in the monitoring program.

DESIRABLE SEAGRASS COVERAGE GOALS ARE ESTABLISHED BY A MANAGEMENT PLAN.

Local and state resource agencies responsible for the conservation and management of seagrasses would establish realistic goals based on the results of item #1 and the logistic and economic constraint! determined by the items #3 and #4 discussed below. Historical data should be consulted to hindcast previous seagrass distributions. These previous distributions would indirectly reveal historical water clarity conditions, perhaps even prior to routine sampling. A map of the water bodies bathymetry would be compared to present seagrass distribution and the estimated *K* value needed to achieve a particular cover could be determined. A cost/benefit analysis should be utilized to determine the feasibility of achieving a desired cover.

WATER QUALITY MONITORING PROGRAM.

Most water quality monitoring programs rely on the simultaneous collection of many parameters, limiting both the intensive (replication) and extensive (spatial coverage) collection of data. Also, because of the size of many of the estuaries the temporal frequency which data are collected may be less than desirable. If light sampling were prioritized as a diagnostic tool and temporarily uncoupled from the demands of other water quality sampling requirements, the number of stations and replications at individual stations could be increased significantly.

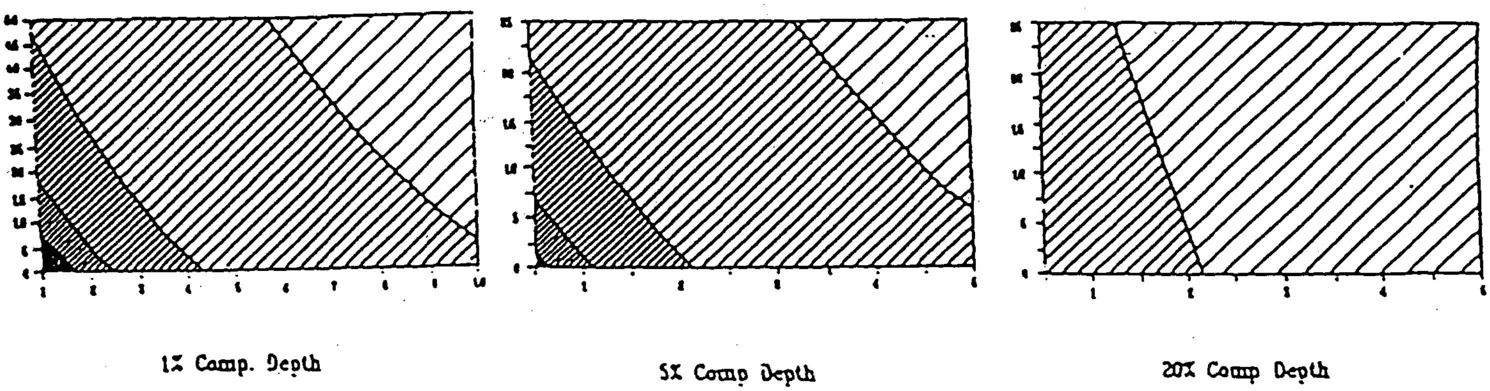
Carefully designed transects along hydrographically oriented water transparency gradients can be used to establish the temporal and spatial variation in background values of *K* (see Chapter 2). Minimum sampling intervals should not exceed five to ten days (approximately weekly). If diagnostic light sampling were uncoupled from other water quality sampling this sample frequency is not an unrealistic goal. The size of an estuary and the number of water quality problem sources will influence the number of water quality problem sources will influence the number of sampling stations, needed for a reasonable survey. Prioritization of troubleshooting efforts and careful planning will be required to optimize the diagnostic sampling effort.

RELATIONSHIP BETWEEN K VALUES AND FUNCTIONAL WATER QUALITY PARAMETERS.

Ultimately it should be the goal of a monitoring program to determine water quality.problem sources. As indicated earlier, the diagnostic *K* value alone does not provide specific enough information about the sources of light attenuation. However, if the *K* value deviate from an established standard value necessary to maintain the percent of incident light at a level which supports seagrasses (desired coverage), then additional water quality sampling could be used to investigate the problem sources. In this process the *K* value sampling is re-coupled to other functional water quality parameters in order to determine which factors are most influential in driving light attenuation. Methods have been developed to formulate models relating spectral light penetration to the concentrations of light-absorbing and scattering materials dissolved and suspended in the water column (Gallegos *et al.*, 1990; Gallegos *et al.*, 1991). These optical models partition the contribution into total scattering and absorption coefficients amongst the various suspended and dissolved materials in the water column. The parameters include total suspended solids (TSS), chlorophyll (Chl), turbidity (NTU) and dissolved organic matter (color) (McPherson and Miller, 1987: Gallegos *et al.*, 1990; Vant, 1990). The individual parameters can then be evaluated in conjunction with each other to estimate their relative effect on the percent of incident light reaching any depth. For example, contour plots of chlorophyll versus total suspended solids can be developed showing the effect of increasing each parameter on the percent of incident light reaching any depth in a water body (Figure A-5). In order to examine which factor has the greatest announce on light attenuation one determines which axis crossed the contour lines faster. The faster the contour lines are crossed, the more likely it will be that water quality management directed at that parameter will have the most benefit for water transparency. Therefore, the sampling effort identifies the most important functional parameter(s) and it also assess the relationship between functional parameters. This approach could improve the quality and effectiveness of regulatory decisions.

Because watersheds differ in their sediment characteristics, freshwater sources, and nutrient regimes, an optical water quality model should be calibrated for each individual water body. Procedure for developing either simple linear regression models or more sophisticated multi-parameter formulations are described in McPherson and Miller (1987), Gallegos *et al.*, (1990) and Gallegos *et al.*, (1991). In summary, the proposed water quality monitoring program for seagrasses is based on a highly sensitive diagnostic parameter (the diffuse attenuation coefficient *K*) that can be quantitatively related to traditionally measured factors through an optical water quality model. Resource managers could use this model to manage the watershed factors through specific regulatory measures.

Figure A-5. Contour plots of predicted photic depths estimated from an optical water quality model using chlorophyll *a* and mineral suspended solids as parameters in the model (Taken from Gallegos *et al.*, 1991).



MANAGEMENT TO REDUCE PROBLEM SOURCES.

Once the problem factors are identified management agencies can take the necessary action to reduce the detrimental effects of the source(s). For readily identifiable point sources the same approach to partitioning the constituents into scattering and absorption described in item #4 can be used to determine how much reduction in discharge would be necessary for that source not to detrimentally alter the transparency of receiving waters (Kirk, 1988). Essentially, either laboratory or *in situ* measurements are used to determine the inherent optical properties of the effluent and the receiving waters. Using dilution calculations, an agency can then estimate the effect of the effluent on the *K* value of the receiving water. The effluent could be wastewater, industrial, stormwater, river, or just about any measurable discharge.

For non-point sources of pollution the problem of identifying the specific source(s) is considerable more difficult. However, the proposed technique would still be capable of identifying a specific parameter or combination of parameters that directly influence transparency. This information would then be available for management agencies to take appropriate regulatory actions rather than to guess, or worse, make no decision at all regarding the management of detrimental causes.

Dissolved inorganic nitrogen (DIN) and (DIP) present a more difficult standard problem. Nutrients affect transparency indirectly either by increasing water column chlorophyll concentrations or encouraging the growth of leaf epiphytes and the associated material attached to the epiphyte complex (Sand-Jensen and Borum, 1983; Howard and Short, 1986; Wetzel and Neckles, 1988). Excessive nutrient loadings also promote the growth of macrophytic algae which can smother the underlying seagrass. Unfortunately, statistical measurements of nutrient concentrations do not reveal the true availability of the element(s) (Fourqurean, 1982). Most of the autotrophic components in coastal systems will utilize nutrients as fast as they are made available, thus, the living biomass and its composition may be more indicative of nutrient status than a snapshot measurement of concentration (Powell *et al.*, 1989).

The chlorophyll parameter, rather than the *K* value, is probably a better diagnostic of nutrient problem. Once values exceed 15-20μg/l chlorophyll can become a significant contribution to light attenuation, depending on the relative contribution of the other constituents (McPherson and Miller, 1987; Vant, 1990; Orth *et al.*, 1991). In the absence of nutrient enrichment, phytoplankton and the water itself make the largest contribution to attenuation in oceanic systems that lack high concentrations of suspended sediments and DOM. But, in coastal water where nutrient loading may be high, and where unpalatable phytoplankton blooms are formed, chlorophyll and other pigments may rival color and TSS in attenuation PAR (for example, recent brown tide events in Long island Sound, New York, and Laguna Madre, Texas).

In addition to water column light attenuation nutrients may stimulate the overabundance of epiphyte attached to the plant leaves. The epiphyte community is an important component of the food chain in seagrass communities, however, there is substantial evidence indicating that under certain conditions the fouling communities will exceed the capacity of the grazers to regulate their abundance (Howard and Short, 1986). Epiphytes and their associated inorganic debris can severely diminish the light reaching the surfaces of fouled leaves (Sand Jensen and Borum, 1983; Neckles, 1991). Nutrient enrichment is frequently invoked as the major cause of fouling, however, complex interactions between many environmental parameters, plant growth rates, and the status of grazer communities all contribute to epiphyte abundance. Models simulating this complexity are difficult to construct, let alone calibrate and verify. Despite these uncertainties, the development and implementation of inorganic nutrient standards is a necessity. Otherwise the distribution of seagrasses predicted from their light requirements and water column attenuation by TSS and DOM may not be realized.

The state of Florida does not have a standard for DIN in Class III waters, however there is a standard for DIP. Assuming that "elemental phosphorus" as stated in the standard language is equivalent to DIP, the standard specifies that phosphorus not exceed 0.1 micrograms per liter in predominantly marine waters. This is an order of magnitude more conservative than the standard (30 micrograms per liter) recommended for waters that will support growth of *Zostera marina* in the polyhaline region of Chesapeake Bay (Orth *et al.*, 1991). This more conservative value would be necessary to minimize eutrophication in the generally oligotrophic waters of south Florida, Florida Bay and the Florida Keys (Fourqurean, 1992). Another important consideration in the phosphorus value is the fact that water bodies overlying carbonate enriched sediments appear to be phosphorus limited. Addition of excessive phosphorus to these environments would stimulate nearly all forms of primary production (Powell *et al.*, 1989; Short *et al.*, 1990). Again, I stress that the measurement of concentration alone does not reflect the availability of a nutrient. The high concentration may actually reflect a post-facto status whereas it is the regeneration rates that determine the system's response. More creative and functional methods of nutrient assessments must be developed in order to set standards and identify problem sources. These may include bioassays of specific water column/epiphyte indicator species, seagrass tissue composition (CNP), delivery ratios of CNP, and isotopic analysis. Discussion of these are beyond the scope of this chapter, however, future applied research should be aimed at determining threshold levels of DIN and DIP which begin to be detrimental to seagrasses.

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APPENDIX III

APPENDIX III

CHESAPEAKE BAY AGREEMENTS: 1992 AMENDMENTS

In 1987, Virginia, Maryland, Pennsylvania, the District of Columbia, the Chesapeake Bay Commission and the U.S. Environmental Protection Agency formally agreed to reduce and control point and non-point sources of pollution to attain the water quality conditions necessary to support the living resources of the Bay.

To achieve this, we agreed to develop, adopt and begin to implement a strategy to equitably achieve by the year 2000 a 40 percent reduction of nitrogen and phosphorus entering the mainstream Chesapeake. We also agreed to reevaluate the 40 percent reduction target based on the results of modeling, monitoring and other information available to us.

<u>BASED UPON THE 1991 NUTRIENT REDUCTION REEVALUATION, WE FOUND THAT:</u>

- We have to achieve significant improvements in water quality and living resources habitat conditions in the mainstream of Chesapeake Bay.
- There is a clear need to expand our program efforts in the tributaries, since most of the spawning grounds and essential habitat are in the tributaries.
- Intensified efforts to control non-point sources of pollution, including agriculture and developed areas, will be needed if we are to meet our 40% nutrient reduction goal.
- ***We are able to demonstrate the link between water quality conditions and the survival and health of critically important submerged aquatic vegetation (SAV).***

- Implementation of the Clean Water Act Amendments will provide additional opportunity to achieve nitrogen reductions.

- Achieving a 40 percent nutrient reduction goal, in at least some cases, challenges the limits of current point and non-point source control technologies.

Therefore, to Further Our Commitments Made in the 1987 Chesapeake Bay Agreement, We Agree:

- To reaffirm our commitments to achieve an overall 40 percent reduction of nitrogen and phosphorus entering the mainstream Chesapeake Bay by the year 2000 and to maintain at least this level of reduction thereafter.

- To amend the water quality goal of the 1987 Chesapeake Bay Agreement to reflect the critical importance of the tributaries in the ultimate restoration of Chesapeake Bay:

"Reduce and control point and non-point sources of pollution to attain the water quality condition necessary to support the living resources of the Chesapeake Bay and its tributaries."

- To develop and begin implementation of tributary-specific strategies by August 1993. These strategies will be designed to:

    1. Meet the mainstream nutrient reduction goals.

    2. Achieve the water quality requirements necessary to restore living resources in both the mainstream and the tributaries.

    3. Incorporate public participation in the development, review, and implementation of the strategies, ensuring the broadest possible public involvement.

    4. Advance both cost-effectiveness and equity.

- ***To use the distribution of submerged aquatic vegetation (SAV) in the Bay and its tidal tributaries, as documented by Bay-wide and other***

aerial surveys conducted since 1970, as an initial measure of progress in the restoration of living resources and water quality.

- To incorporate into the Nutrient Reduction Strategies an air deposition component which builds upon the 1990 Amendments to the federal Clean Air Act and explores additional implementation opportunities to further reduce airborne sources of nitrogen entering Chesapeake Bay and its tributaries.

- To continue to explore improved technologies that may be cost-effective in attaining further nutrient reductions.

- To explore cooperative working relationships with the other three basin states (New York/West Virginia/Delaware) in the development of tributary-specific strategies for nutrient reduction.

The two critically important goals addressing the use of submerged aquatic vegetation as a characteristic to measure health in Chesapeake Bay.

APPENDIX IV

GLOSSARY

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GLOSSARY

Adenosine Triphosphate (ATP). A cellular constituent that functions as a phosphate donor. An important energy compound in metabolism.

Algae. Aquatic non-flowering plants that lack roots and use light energy to convert carbon dioxide and inorganic nutrients such as nitrogen and phosphorus into organic matter by photosynthesis. Common algae include dinoflagellates, diatoms, seaweeds, and kelp.

Anaerobic. A process occurring in the absence of free oxygen.

Anoxic. A condition in which oxygen is absent.

Attenuation. A process by which a compound is reduced in concentration over time or distance through absorption, degradation, or transformation.

Autotrophy. The fixation of light energy from the sun or use of inorganic compounds for food, as by plants and some bacteria.

Best Management Practices (BMP). A method, activity, maintenance procedure, or other management practice for reducing the amount of pollution entering a water body. The term originated from the rules and regulations developed pursuant to the federal Clean Water Act (40 CFR 130).

Bio-accumulation. The process by which a contaminant accumulates in the tissues of an individual organism. For example, certain chemicals in food eaten by a fish tend to accumulate in its liver and other tissues.

Biochemical Oxygen Demand (BOD). The amount of dissolved oxygen required to meet the metabolic rate needs of anaerobic microorganisms in water rich in organic matter, such as sewage.

Biota. Animal and plant life characterizing a given region. Fauna and flora together.

Build-out Analysis. A parcel-by-parcel analysis to estimate the total number of existing and developable units, based on current zoning and other land-use regulations. Such an analysis is essential for managing and limiting impacts of growth.

Carcinogen. A cancer-causing substance.

Coastal Zone. Florida statutes (FL. 380.19) define the coastal zone as "that area of land and water from the territorial seaward to the most inland extent of maritime influences."

Coexistence. Occurrence of two or more species in the same habitat; usually applied to potentially competing species.

Community. An association of interacting populations, usually delineated by their interactions or by spatial occurrence.

Compensation Point. The light intensity at which the amount of carbon dioxide released in respiration equals the amount used in photosynthesis, and the amount of oxygen released in photosynthesis equals the amount used in respiration. Usually refers to the lower limit of the euphotic zone.

Contaminant. A pollutant to a water body. A substance which is not naturally present in the environment or is present in unnatural concentrations that can, in sufficient concentration, adversely alter an environment.

Department of Environmental Protection. The state agency responsible for the permitting, regulation and management of natural resources. This agency is also responsible for the scientific research (biological, chemical, physical) and management of the state's natural resources.

Detritus. Freshly dead or partially decomposed organic matter.

Drainage Basin. The land that surrounds a body of water and contributes fresh water, either from streams, groundwater, or surface water runoff, to that body of water.

Dredging. Any physical digging into the bottom sediment of a water body. Dredging can be done with mechanical or hydraulic machines, and it changes the shape and form of the bottom. Dredging is conducted periodically in the Indian River Lagoon system to maintain navigational channels that would otherwise fill with sediment and obstruct ship passage.

Ecosystem. A community of living organisms interacting with one another and with their physical environment, such as mangroves, a salt marsh or and estuary. The Indian River Lagoon system is considered a sum of these interconnected ecosystems.

Eelgrass (*Zostera marina*). The most widely distributed seagrass in North America. It occurs on the Pacific Coast from Alaska to Baja California and into Mexico and on the Atlantic Coast from southern Greenland to South Carolina. *Zostera* generally grows in shallow lagoons and bays, but may occur up to 50 meters deep. Eelgrass beds are an important habitat and nursery for fish, shellfish and waterfowl.

Effluent. The outflow of water, with or without pollutants, usually from a pipe.

Environmental Protection Agency (EPA). The federal agency principally responsible for administering the Clean Water Act, the National Estuary Program, CERCLA, Superfund, and other major federal environmental programs.

Enzyme. An organic catalyst, produced by living cells, each kind determining a specific chemical reaction.

Epiphyte. A plant which grows nonparasitically on another plant or some nonliving structure.

Estuary. A semi-enclosed coastal water body which has a free connection to the open sea and within which seawater is measurably diluted with freshwater.

Euphotic Zone. The uppermost portion of a body of water which receives sufficient light penetration for photosynthesis (see Compensation Point).

Eutrophic. Referring to a body of water with abundant nutrients and high productivity.

Eutrophication. The process of nutrient enrichment in a water body. In marine systems, eutrophication results principally from nitrogen inputs from human activities such as sewage disposal and runoff from fertilized agricultural land. Such inputs may stimulate algal blooms and bacteria growth, which can contribute to the depletion of oxygen in the water, causing anoxic condition and eventual fish kills.

Goal. A general statement describing what is to be achieved in the future. Goals reflect and consensual vision for a specific or general resource.

Habitat. The specific place or environment where a particular plant or animal lives. An organism's habitat must provide all the basic requirements for life and should be free of harmful contaminants. Optical habitats in the Indian River Lagoon include mangroves, beaches, marshes, coral reefs, mudflats and the water itself.

Hypoxia. A condition in which oxygen is deficient.

Johnson's seagrass (*Halophila johnsonii*). Is a rare seagrass limited in distribution to the east coast of Florida between Biscayne Bay and Sebastian Inlet. The physical habitat for the species is both the shallow intertidal and deeper subtidal zones. Johnson's grass is the least common of all seagrass species within its range. The seagrass is also the rarest species in the genus *Halophila*.

Lagoon. A shallow body of water which is separated from the sea by a sandbar, barrier beach, or coral reef where salt water from the sea and fresh surface water runoff from the land meet and mix.

Loading. The total amount of material entering a system from all sources.

Manatee Grass (*Syringodium filiforme*). A marine flowering plant that grows in both intertidal and subtidal regions. Manatee grass is one of seven species of seagrass found in the Indian River Lagoon system. It is easily recognized by its cylindrical leaves.

Mangrove. A tropical aquatic shrub which grows partially submerged. They have stilt-like roots and stems and form dense thickets in muddy tidal regions. Mangroves offer an important habitat for fish, shellfish, and crustaceans.

Metals. Elements found in rock and minerals that are naturally released to the environment by erosion, as well as human activity. Certain metals, such as mercury, lead, zinc, and cadmium, are of environmental concern because they are released to the environment in excessive amounts and have detrimental effects on the ecosystem.

National Estuary Program (NEP). A state grant program within the U.S. Environmental Protection Agency established to designate estuaries of national significance and to incorporate scientific research into planning activities.

Non-point Source Pollution. Pollution that is generated over a relatively wide area and may disperse into the lagoon through storm drains or land runoff instead of a pipe. Non-point source pollution include stormwater runoff, leaking septic systems, and overboard waste from boats and ships.

Nutrients. Any substance absorbed by a plants that is used in its metabolism. Mineral nutrients usually refer to inorganic substances taken from soil and water. Excessive amount of nutrients, including nitrogen and phosphorus, may result in nutrient loading leading to oxygen depletion and water degradation.

Oligotrophic. Referring to a body of water with a low nutrient content and low productivity, usually characterized by extremely clear water.

Paddle Grass (*Halophila decipiens*) A marine flowing plant that has certain morphological and structural features enabling it to maximize its light harvesting capacity to a low light environment. Compared to other seagrasses, it is relatively short lived, with a high fecundity and rhizome elongation rate, allowing it to colonize disturbed sites and recover from perturbations within existing meadows.

Pathogen. An agent present, such as a virus or fungus, that can cause disease in humans. Pathogens can be present in municipal, industrial, and nonpoint source discharges into the Indian River Lagoon system.

Photoautotroph. An organism that utilizes sunlight as its primary energy source for the synthesis of organic compounds.

Photosynthesis. The synthesis of organic matter from inorganic substrates, using light as a source of energy and producing oxygen as a by-product.

Plankton. Passively floating or weakly motile aquatic plant (phytoplankton) or animal (zooplankton).

Point Source Pollution. Pollution originating at a particular place, such as a sewage treatment plant, effluent outfall pipe or other discharge pipes into a water body.

Resource. A substance or object required by an organism for normal maintenance, growth, and reproduction. If the resource is scarce relative to demand, it is referred to as a limiting resource. Non-renewable resources (such as space) occur in fixed amounts and can be fully utilized; renewable resources (such as food) are produced at a fixed rate, with which the rate of exploitation attains an equilibrium.

Respiration. The complex series of chemical reactions in all living organisms by which the energy in food is made available for use. In aerobic respiration, free oxygen is utilized and carbon dioxide is released; in anaerobic respiration, free oxygen is not required.

Runoff. The part of precipitation which as surface run-off flows off the land without sinking into the soil and the part that enters the ground and passes through into surface streams as groundwater run-off.

Salinity. The quality of saltiness in seawater or fresh water, most commonly expressed in parts of dissolved salt per 1000 parts of water (i.e. parts per thousand, ppt).

Seagrass. Flowering plants that live underwater. Like land plants, seagrasses produce oxygen. The depth at which seagrasses are found is limited by water clarity because they require light to grow. They are important to ecosystems as they help maintain water clarity by trapping suspended sediments, stabilizing the bottom with their root system, and providing a nursery habitat for fish, shellfish and crustaceans.

Shellfish. An aquatic animal, such as a mollusc (clam or snail) or crustacean (crab, shrimp, or lobster) which has a shell-like exoskeleton.

Shoal Grass (*Halodule wrightii*). Shoal grass is the most abundant of the seven species of seagrass found in the Indian River Lagoon-system. *Halodule* is widely distributed along the coast of tropical seas of the Atlantic and Indo-Pacific regions. Its northern limit for this species is the Outer Banks of North Carolina along the Atlantic coast. It is an early colonizer of disturbed areas and ranges from subtidal to intertidal zones. It commonly grows in areas too shallow for other species.

Standard. A standard is an acknowledged basis for comparing or measuring, criterion; a degree or level of requirement.

Star Grass (*Halophila englemanni*). A marine flowering plant that has adapted to low light conditions and living under plant canopies. *H. englemanni* gets it's common name from the distinctive star-like arrangement of its leaves.

Storm Drain. A system of gutter, pipes, and ditches used to carry stormwater from the land to streams, ponds and the Indian River Lagoon system. Storm drains carry variety of substances ranging from lawn clippings to motor oil.

Stormwater. Precipitation that is often routed into a storm drain system to prevent flooding.

Suspended Solids. Organic or inorganic particles that are suspended in and carried by the water. Such examples include sand and mud, as well as wastewater.

Toxic. Poisonous, carcinogenic, or other-wise directly harmful to life.

Turbidity. The clouding of a naturally clear liquid due to suspension of fine solids. Because turbidity reduces the amount of light penetrating the water column, high turbidity levels are harmful to aquatic life.

Turtle Grass (*Thalassia testudinum*). Is the most abundant marine phanerogam in the tropical western Atlantic region. In the U.S. it occurs from Sebastian Inlet, Florida, south around the entire arc of the Gulf of Mexico to southern Texas. *Thalassia* has strong, erect leaves and a deep root structure 5 to 10 cm in the substrate. It grows in areas from quiet, shallow lagoons to open water up to 30 meters deep.

Wastewater. Water that has come into contact with pollutants as a result of human activities and is not used in a product, but is discharged as a waste stream.

Water Column. The water, lake, estuary, or ocean which extends from the bottom sediments to the surface. Water column contains dissolved and particulate matter, and is the habitat for plankton, fish, and marine mammals.

Wetland. Habitats where the influence of surface water or groundwater has resulted in the development of plant or animal communities adapted to aquatic or intermittently wet conditions. Wetlands include tidal flats, shallow sub-tidal areas, swamps, marshes, wet meadows, bogs, and similar areas.

Widgeon Grass (*Ruppia maritima*). Is capable of growing in a wide range of salinities, from fresh to saltwater. It is very tolerant of cold water, growing well into the winter months. It is widespread along both coasts of the U.S. and throughout Europe. *Ruppia* has long, thread-like, alternating leaves, up to 10 cm long. However, its most distinguishing feature is its umbellate cluster of four to six fruits per productive shoots. These shoots may grow to a length of over 1 meter long.